# AN INTEGRATED SEDIMENTOLOGICAL, ICHNOLOGICAL AND SEQUENCE STRATIGRAPHIC STUDY IN THE DEVONIAN–CARBONIFEROUS BAKKEN FORMATION OF SUBSURFACE SOUTHEASTERN SASKATCHEWAN

A thesis Submitted to the College of

Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy

in the Department of Geological Sciences

University of Saskatchewan

Saskatoon

By

Solange Angulo-Saldiña

© Copyright, Solange Angulo-Saldiña, January 2010. All rights reserved

## PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis/dissertation or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis/dissertation.

## DISCLAIMER

Reference in this thesis to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan, and shall not be used for advertising or product endorsement purposes.

Requests for permission to copy or to make other uses of materials in this thesis/dissertation in whole or part should be addressed to:

Head of the Department of Geological sciences

University of Saskatchewan

Saskatoon, Saskatchewan, S7N 5E2

Canada

OR

Dean

College of Graduate Studies and Research

University of Saskatchewan

107 Administration Place

Saskatoon, Saskatchewan, S7N 5A2

Canada

## ABSTRACT

In spite of the economic importance of the Bakken Formation as one of the most prominent oil-producing units in North America (Canada and USA), an integrated sedimentological, ichnological and sequence stratigraphic analysis of the Upper Devonian - Lower Carboniferous Bakken Formation is presented for the first time in this thesis.

The Bakken Formation has been subdivided into three members: lower, middle and upper. The lower and upper members are homogeneous and consist of only one sedimentary facies (facies 1); in contrast, the middle member is much more heterogeneous, both vertically and laterally, and comprises several sedimentary facies (facies 2 to 10). For this project, sixty-two well-cores from southeastern Saskatchewan were examined in detail. Eleven sedimentary facies were defined based on lithology, sedimentary structures and trace-fossil content (F1 to F11). From these, two facies were subdivided into subfacies (F3 and F8). These facies were grouped into two facies associations: open marine and brackish-water marginal marine. According to the sequence-stratigraphic framework, the orientation and geometry of the sedimentary bodies and the distribution of the sedimentary facies, the brackish-water interval is interpreted as a marginal-marine embayment.

The Upper Devonian–Lower Carboniferous Bakken Formation records a complex depositional history involving several relative sea-level changes and open marine and brackish-water marginal-marine conditions. The depositional history of the Bakken can be summarized within three systems tracts: (1) a lower transgressive systems tract, which comprises black shelf shales (facies 1) of the lower part of the lower member; (2) a highstand systems tract, which embraces from bottom to top black shelf shale (facies 1) of the upper part of the lower member, and lower-offshore muddy siltstone (facies 2), upper-offshore sandy siltstone (subfacies 3A), offshore-transition silty very fine-grained sandstone (facies 4) and locally lower-shoreface, silty, very fine-grained sandstone (facies 5) of the lower part of the middle member; and (3) an upper transgressive systems tract, which encompasses barrier-bar fine-grained sandstone (facies 6), margin-bay, very fine-grained sandstone (subfacies 8A), very thinly laminated mudstone, siltstone and very fine-grained sandstone (facies 9), distal-bay, thinly interlaminated mudstone and very fine-grained sandstone (facies 10), very fine-grained sandstone (subfacies 8B), tidal-flat

very fine-grained sandstone (subfacies 8C), wave-dominated tidal-flat very fine-grained sandstone (facies 7), transgressive lag (facies 11), and upper-offshore siltstone interbedded with very fine-grained sandstone (subfacies 3B) of the upper part of the middle member, and black shelfal shale (facies 1) of the upper member.

Deposition of the Bakken Formation was controlled mostly by salinity, oxygen content and storm action. While open-marine deposits are generally characterized by high degrees of bioturbation, moderate ichnodiversity and the "distal" *Cruziana* ichnofacies, brackish-water marginal-marine deposits are distinguished by low levels of bioturbation, lower ichnodiversity, and the "impoverished" *Cruziana* ichnofacies. The lack of bioturbation, black color, high organic matter content, thin lamination, and scarce benthic fauna indicate anoxic conditions in shelf deposits, whereas the rest of the open-marine sediments accumulated under well-oxygenated conditions. Depending on the frequency and intensity of storms, tempestites were preserved or not in the upper-offshore deposits.

Based on the petrophysical characterization of the sedimentary facies of the Bakken Formation, facies 6, 7, 4 and subfacies 8C have the best reservoir rock quality with the highest porosities (8.6% to 12%) and permeabilities (0.09 md to 0.27 md). Lithology, diagenesis and bioturbation played a key control on the reservoir quality of the rock. However, the importance of the spatial distribution of the sedimentary facies in reservoir potential should not be overlooked. While facies 4, deposited in an open-marine realm, has the best reservoir potential in southeastern Saskatchewan due to its wide distribution; facies 6, 7 and subfacies 8C, deposited in the brackish-water dominium, can constitute good local targets.

## ACKNOWLEDGEMENTS

First and foremost I want to give special thanks to my supervisor Dr. Luis Buatois, for his guidance, his support, time, knowledge and patience. I also benefited from the contribution of my advisory committee: Dr. Gabriela Mángano, Dr. Robin Renaut, Dr. Jim Merriam and Dr. Chris Hawkes.

I want to give special thanks to Gabriela Mángano and Luis Buatois not only for their over standing academic support, but also for their understanding, for their human quality and for providing a warm atmosphere for all their students they take under their guidance.

I am very thankful to Saskatchewan Energy and Resources and the University of Saskatchewan for providing financial support for this project. Additional funding was provided by the American Association of Petroleum Geologists (AAPG) and the International Association of Sedimentologists (IAS).

I am also very grateful to the Geological Subsurface Laboratory staff in Regina, in particular to Melinda Yurkowski, Chris Gilboy, Dan Kohlruss, Erik, Nickel, Chao Yang, Tyler Music, and all the technical team that displayed the cores for this study at no cost; without their support this project would have not been possible.

This project also benefited from discussions with Gabriela Mángano, Kim Kreis, John Lake, Andrew Nimegeers, James MacEachern, Carol Brown and Fran Haidl.

I would like to thank María Vélez and Carlos Londoño for providing free accommodation during core work in Regina and receiving me in their house as one member of the family.

I want to give special thanks to my parents, Celeste Saldiña and Luis Angulo, for their unconditional support, for their encouragement, for believing on me, even when my projects overcome me. I am also very grateful to my husband, Chris Conrad for his patience, his support and his understanding, especially at the final stage of my thesis. I am also thankful to my sister, Beatriz Angulo, and my brother, Fernando Angulo, for being always there when I have needed them.

I want to thank to fellow graduate students Luis Quiroz, Patricio Desjardins, Robin Smith, and Jenny Scott for their support during this learning experience, in which we all shared knowledge and counted with each other when we needed it.

## DEDICATION

To those who have marked my life, who have contributed to be who I am, from whom I have been enriched and have grown, sharing experiences while we have walked together. To those who have inspired me to find my own path.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| BI | Bioturbation index |
| HST | Highstand systems tract |
| LST | Lowstand systems tract |
| MFS | Maximum flooding surface |
| SB | Sequence boundary |
| TS | Transgressive surface |
| TST | Transgressive systems tract |

# 1. INTRODUCTION

The exceptional utility of ichnology is increasingly being recognized as a powerful tool for paleoenvironmental reconstructions. Biogenic structures effectively provide an *in situ* record of environments and environmental changes, based on factors that influence benthic organisms (Bromley, 1996; Pemberton et al., 2001; McIlroy, 2004; MacEachern and Gingras, 2007; Buatois and Mángano, 2011). Trace fossils record the behavior of the producers, typically as a response to subtle changes in environmental parameters, such as salinity, oxygen, and food supply (e.g., Mángano et al., 2002), which are not commonly recorded in the original sedimentary fabric. Therefore, integration of sedimentology and ichnology provides a more accurate picture of depositional conditions.

In spite of the economic importance of the Upper Devonian–Lower Carboniferous Bakken Formation as an oil producing unit in North America (USA and Canada), no integrated sedimentological, ichnological and sequence stratigraphic analysis has yet been presented. According to previous sedimentological interpretations (Christopher, 1961; LeFever et al., 1991; Smith et al., 1995; Smith and Bustin, 1996, 2000; Kreis et al., 2005, 2006, Kohlruss and Nickel, 2009), the Bakken Formation was deposited entirely under fully marine conditions. However, the sedimentological and ichnological analysis of cores in southeastern Saskatchewan reveals that deposition of the middle member occurred not only under fully marine but also brackish-water conditions (Angulo et al., 2008; Angulo and Buatois 2010, 2012, in press). Detailed analysis of the brackish-water deposits demonstrates that these cannot be interpreted following classic estuarine or deltaic models. Consequently, these are interpreted as an embayment with limited or intermittent connection to the open sea.

Recent discoveries in northeastern Montana and North Dakota have notably increased attention from the petroleum industry, which has drastically augmented the drilling of oil wells in southeastern Saskatchewan in the last five years [by 2004 less than 80 wells had been drilled, by July 2008, this number has risen to 895 wells (Dan Kohlruss, written communication, 2011)].

The Bakken Formation is restricted to the subsurface of the Williston Basin in North Dakota, Montana, Manitoba and Saskatchewan and, as suggested by conodont biostratigraphy, was deposited during the Late Devonian and Early Mississippian (Hayes, 1985; Karma, 1991).

Although generally less than 28 m thick in southeast Saskatchewan, the Bakken Formation records a complex depositional history, involving several sea-level changes and both open-marine and brackish-water marginal-marine deposits. In addition, it represents a “perfect” hydrocarbon system, comprising the source rock, reservoir rock, and cap rock all within the same formation (Halabura et al., 2007).

The Bakken Formation is subdivided into three members: lower, middle and upper. The lower and the upper members are homogeneous and consist of only one sedimentary facies (black shale). In contrast, the middle member is much more heterogeneous and variable, and comprises several sedimentary facies (calcareous to dolomitic muddy siltstone, silty sandstone, and calcareous and non-calcareous sandstone, siltstone and mudstone). In turn, the middle member has been subdivided into units A, B and C in this study.

The study area is located in southeastern Saskatchewan (48° 59’–49° 57’ latitude N, 102 16’–105 20’ longitude W) covering approximately 29,900 $km^2$.

## 1.1. RESEARCH OBJECTIVES

The main goal of this research is to integrate ichnological and sedimentological data to reconstruct the paleoenvironmental and paleogeographic evolution of the Bakken Formation during the Late Devonian–Early Mississippian within a sequence-stratigraphic framework, and to establish the interrelationships among sea-level changes, the temporal and spatial distribution of depositional environments, and biogenic structures.

The specific objectives of this research were:

- Describe and interpret the sedimentary facies of the Bakken Formation based on core analysis
- Identify facies associations in terms of sedimentary processes and environments
- Characterize the trace fossils and their paleoenvironmental implications
- Prepare maps to determine the distribution of the sedimentary facies in the study area
- Propose a depositional model taking into account the sedimentological and ichnological characteristics of the Bakken Formation and their evolution through time within a sequence-stratigraphic framework

## 1.2. METHODOLOGY

Although eighty-one well cores (approximately 1490 meters of total length) of the Bakken Formation were examined in Saskatchewan, this project is based on the analyses of sixty-two well cores (approximately 1330 meters of total length) from southeastern Saskatchewan (Table 1.1). Core analyses were made in the Geological Subsurface Laboratory in Regina during three summers (2007-2009). Cores were slabbed in order to provide a clear and detailed view of the sedimentary facies. 1872 core photographs were taken during this study. Due to the lack of exposures of the Bakken, two outcrops [Jura Creek (type section) and Crowsnest Lake (roadcut on Highway 3)] of the partially coeval Exshaw Formation in Alberta were analyzed to provide a better understanding of the sedimentary facies and depositional dynamics.

Eleven sedimentary facies (facies 1 to 11) were defined based on lithology, sedimentary structures, trace-fossil content and bioturbation index. Facies 3 and 8 were in turn, subdivided into subfacies 3A and 3B, and subfacies 8A, 8B and 8C, respectively. Estimation of bioturbation index (BI) follows the scheme of Taylor and Goldring (1993). In this scheme, BI=0 is characterized by no bioturbation (0%). BI=1 (1 to 4%) is for sparse bioturbation with few discrete traces. BI=2 (5 to 30%) is represented by low bioturbation in sediment that still has preserved sedimentary structures. BI=3 (31 to 60%) describes an ichnofabric with discrete trace fossils, moderate bioturbation, and still-distinguishable bedding boundaries. BI=4 (61 to 90%) is represented by intense bioturbation, high trace-fossil density, common overlap of trace fossils, and primary sedimentary structures are mostly erased. BI=5 (91 to 99%) is characterized by sediment with completely disturbed bedding and intense bioturbation. BI=6 (100%) is for completely bioturbated and reworked sediment, related to repeated overprinting of trace fossils.

The sedimentary facies defined in this study were grouped into two facies associations: (1) open marine (facies 1 to 5, facies 11), and (2) brackish-water marginal-marine embayment (facies 6 to 10). The environmental zonation for open-marine settings is based on MacEachern et al. (1999), being the shelf located below the storm-wave base, the offshore between the storm-wave base and the fair-weather wave base, the shoreface between the fair-weather wave base and the low-tide line, the foreshore between the low and high-tide line, and the backshore above the high-tide line. On the other hand, the offshore transition is interpreted as a gradational zone between the offshore and the shoreface. The environmental zonation for the brackish-water

Table 1.1 – List of the sixty-two cored wells examined in this study. Well numbers on the table correspond to well locations shown in maps of the study area (Chapters 1 to 3).

| N° | Well ID | N° | Well ID |
|---|---|---|---|
| 1 | 101/12-29-001-05W2/00 | 32 | 101/16-35-006-14W2/00 |
| 2 | 131/04-16-001-08W2/00 | 33 | 101/03-09-006-16W2/00 |
| 3 | 141/15-31-001-09W2/00 | 34 | 101/03-25-006-16W2/00 |
| 4 | 121/04-02-001-10W2/00 | 35 | 101/01-20-006-19W2/00 |
| 5 | 101/10-15-001-16W2/00 | 36 | 101/05-04-006-24W2/00 |
| 6 | 101/12-21-001-16W2/00 | 37 | 101/03-03-006-25W2/00 |
| 7 | 101/01-31-001-20W2/00 | 38 | 111/01-25-007-05W2/00 |
| 8 | 101/03-20-002-16W2/00 | 39 | 111/16-29-007-07W2/00 |
| 9 | 131/10-01-002-19W2/00 | 40 | 101/03-04-007-11W2/00 |
| 10 | 101/06-13-002-19W2/00 | 41 | 101/01-11-007-11W2/00 |
| 11 | 101/14-15-002-23W2/00 | 42 | 191/07-12-007-11W2/00 |
| 12 | 141/09-05-003-06W2/00 | 43 | 101/01-36-007-11W2/00 |
| 13 | 141/15-31-003-11W2/00 | 44 | 101/06-09-007-13W2/00 |
| 14 | 141/07-32-003-11W2/00 | 45 | 101/16-10-007-15W2/00 |
| 15 | 101/03-18-003-13W2/00 | 46 | 101/15-29-007-15W2/00 |
| 16 | 101/08-23-003-24W2/00 | 47 | 101/05-14-007-23W2/00 |
| 17 | 191/13-34-004-09W2/00 | 48 | 111/01-24-007-23W2/00 |
| 18 | 101/08-20-004-14W2/00 | 49 | 101/13-30-007-23W2/00 |
| 19 | 101/06-11-004-21W2/00 | 50 | 111/07-06-008-08W2/00 |
| 20 | 101/09-18-004-22W2/00 | 51 | 121/05-05-008-09W2/00 |
| 21 | 111/01-14-005-09W2/00 | 52 | 101/07-11-008-10W2/00 |
| 22 | 121/05-04-005-11W2/00 | 53 | 101/01-10-008-11W2/00 |
| 23 | 141/09-13-005-13W2/00 | 54 | 101/08-11-008-14W2/00 |
| 24 | 101/13-32-005-17W2/00 | 55 | 141/03-23-009-03W2/00 |
| 25 | 101/06-20-005-24W2/00 | 56 | 131/13-21-009-07W2/00 |
| 26 | 101/09-36-005-25W2/00 | 57 | 101/06-36-010-03W2/00 |
| 27 | 141/02-18-006-05W2/00 | 58 | 101/15-25-010-08W2/00 |
| 28 | 101/06-18-006-10W2/00 | 59 | 101/11-02-010-13W2/00 |
| 29 | 101/07-28-006-11W2/00 | 60 | 121/12-05-011-05W2/00 |
| 30 | 101/03-36-006-12W2/00 | 61 | 101/06-30-011-09W2/00 |
| 31 | 101/05-31-006-13W2/00 | 62 | 130/15-20-011-14W2/00 |

marginal-marine embayment is based on MacEachern and Gingras (2007), in which restricted bays are subdivided into distal-bay, bay-margin and bay-mouth deposits. Core descriptions were calibrated with geophysical well logs (gamma ray, sonic and resistivity) obtained from the software GeoScout, version 7.

For a better understanding of the aerial distribution of the sedimentary facies, isochore maps of the facies and subfacies were made. These maps were prepared using the software Surfer, version 8.08, with kriging as the gridding method. Since the open-marine sedimentary facies are restricted to a specific stratigraphic interval, isochore maps of these facies represent discrete occurrences. In contrast, brackish-water marginal-marine facies commonly recur vertically and tend to interfinger with each other. Thus, isochore maps of these facies instead reflect the net thickness. However, although facies 1 recurs in two different stratigraphic intervals (lower and upper members), two isochore maps were made, one for the lower member and another for the upper member.

In addition, a petrophysical characterization of the sedimentary facies of the middle member was carried out. The only wells used were those for which accurate calibration of the core analyses with sedimentary facies was possible. Accordingly, only thirty-two logged well cores were used from the sixty-two well cores analyzed. Once the calibration of the sedimentary facies with the core analyses was achieved, the porosity and permeability ($k_{max}$) values were grouped for each facies and subfacies, and the arithmetic mean of the porosity and the harmonic mean of the permeabilities, and their respective standard deviations were calculated. Furthermore, cross-plot charts of porosity versus permeability were made for each sedimentary facies and subfacies (Appendix). Core analyses were facilitated by the Saskatchewan Geological Survey in Regina.

Taking into account the ichnological and sedimentological characteristics of the sedimentary facies, the most important environmental parameters that controlled deposition of the Bakken Formation were established. Additionally, the sedimentary environments and subenvironments present during deposition of Bakken were interpreted. Additionally, paleogeographic sketches illustrating the geological evolution of the Bakken were made.

As part of the agreement with the funding agency (Saskatchewan Energy and Resources) four articles were published in *Summary of Investigations* of the Saskatchewan Geological Survey [“Paleoenvironmental and sequence-stratigraphic reinterpretation of the Upper Devonian–Lower Mississippian Bakken Formation of subsurface Saskatchewan integrating sedimentological and ichnological data” (Angulo et al., 2008); “Sedimentological and ichnological aspects of a sandy low-energy coast: Upper Devonian–Lower Mississippian Bakken

Formation, Williston Basin, southeastern Saskatchewan" (Angulo and Buatois, 2009); "Sedimentary facies distribution of the Upper Devonian–Lower Mississippian Bakken, Formation, Williston Basin, southeastern Saskatchewan: implications for understanding reservoir geometry, paleogeography, and depositional history" (Angulo and Buatois, 2010); "Petrophysical characterization of sedimentary facies from the Upper Devonian–Lower Mississippian Bakken Formation in the Williston Basin, southeastern Saskatchewan" (Angulo and Buatois, 2011)]. These articles expand different aspects of this thesis.

## 1.3. THESIS STRUCTURE

The following three chapters of this thesis were prepared as manuscripts intended for publication. Accordingly, each chapter contains its own introduction, development, conclusions and references. Therefore, each can be treated as a stand-alone document.

Chapter 2, "Integrating depositional models, ichnology and sequence stratigraphy in reservoir characterization: the middle member of the Devonian–Carboniferous Bakken Formation of subsurface southeastern Saskatchewan revisited" presents a new depositional model for the Bakken Formation explaining the sedimentological and ichnological characteristics of this unit within a sequence-stratigraphic framework. According to this model, initial deposition in the Bakken (lower member) is related to a transgression, which passed into a highstand systems tract, recording the progradation of the shoreline. Subsequently, a drastic relative sea-level drop occurred and the area was exposed to by-pass and erosion. As the relative sea level started rising, a brackish-water marginal-marine embayment was formed, followed by the re-establishment of fully marine conditions in the entire area during the late stage of the transgression. Comparison of this model with previous interpretations, such as lowstand offshore-shoreface complex (Smith and Bustin, 2000), normal-regressive offshore-shoreface complex and incised estuary (Angulo et al., 2008), and falling-stage shoreface complex (Kohlruss and Nickel, 2009) is also presented in this chapter. In addition, the implications of this new model in reservoir characterization, based on petrophysical evaluation and detailed isochore maps of the facies, are discussed in this chapter.

Chapter 3, "Ichnology of a Late Devonian–Early Carboniferous low-energy seaway: the Bakken Formation of subsurface Saskatchewan, Canada: Assessing paleoenvironmental controls and biotic responses” focuses on the ichnofauna of the Bakken Formation, and analyzes the environmental parameters during deposition and the associated biotic response. In contrast with previous interpretations which suggest open-marine conditions for the entire unit, integration of ichnological and sedimentological data provide evidence that deposition of the Bakken Formation occurred in two depositional settings: open marine and brackish-water marginal marine. Salinity, oxygen content, and storm action were the most important factors controlling the style of bioturbation and the ichnofossils distribution. Open-marine sedimentary facies are generally distinguished by high bioturbation index, relatively high ichnodiversity and the “distal” *Cruziana* ichnofacies. In contrast, brackish-water sedimentary facies are characterized by the absence of bioturbation or a low bioturbation index, lower ichnodiversity and the “impoverished” *Cruziana* ichnofacies. Lack of bioturbation in the shelf deposits of the lower and upper members is attributed to anoxic conditions, while the rest of the open-marine deposits records well-oxygenated conditions. Finally, the two contrasting patterns of tempestite preservation in the upper-offshore deposits between the highstand and transgressive systems tracts are attributed to differences in the intensity and frequency of the storms.

Chapter 4, “Delineation of brackish-water embayments in the stratigraphic record: the Upper Devonian–Lower Carboniferous Bakken Formation, southeastern Saskatchewan, Canada” presents a detailed characterization of the brackish-water interval of the middle member of the Bakken Formation. Description, distribution, and interpretation of the sedimentary facies recognized in these deposits are presented. Three alternative interpretations for the sedimentary environment of this interval are discussed: deltaic, estuarine and embayment. Based on the sequence-stratigraphic framework, the orientation and geometry of the sedimentary bodies and the distribution of the sedimentary facies, the brackish-water deposits are interpreted as formed in a marginal-marine embayment with limited or intermittent connection to the sea water. Finally, this chapter examines diagnostic criteria for the recognition of brackish-water embayments in the stratigraphic record. The Bakken Formation records an example of the high complexity of the internal sedimentary facies architecture that may characterize these deposits due to the migration of the barrier bar and its associated back-barrier deposits as the relative sea level fluctuated.

Chapter 3 has been published in *Palaegeography, Palaeoclimatology, Palaeoecology* (Angulo and Buatois, 2012), while Chapter 2 has been accepted for publication for the *American*

*Association of Petroleum Geologists Bulletin* (Angulo and Buatois, in press). Chapter 4 will be submitted to *Sedimentology*.

Finally, cross-plot charts of the porosity versus permeability of the sedimentary facies and subfacies of the middle member, and the number of wells and plug values used for the petrophysical characterization, are shown in the Appendix.

## 1.4. RESEARCH IMPACT

A more accurate sedimentological model for the Bakken Formation would improve understanding of the distribution of sedimentary facies, lateral and vertical changes in facies, geometries of the sedimentary bodies, and distribution of the prospective rocks in the area. This has profound implications for hydrocarbon exploration and subsequent production because reservoir quality is largely influenced by external geometry and distribution of depositional facies. Documentation of sedimentary facies variability may help to constrain fluid behavior, and porosity and permeability heterogeneities. Accordingly, integration of trace fossils and sedimentary facies within a sequence-stratigraphic framework was used to define favorable conditions for reservoir development, quality, and continuity, with significant implications for the petroleum-industry in both exploration and production.

Marginal-marine embayments constitute a common element in modern coastlines. Nevertheless, relatively few examples of this depositional setting have been documented in the literature (e.g., Hubbard et al., 1999; Hayes et al., 1994; Geier and Pemberton, 1994; Desjardins et al., 2009, 2010; Yoshida et al., 2004). This paradox may be attributed to the difficulty in their recognition in the stratigraphic record. Even though significant effort has been made in the recent decades to understand the processes and the sedimentary facies that occur in modern marginal-marine embayments, the diagnostic criteria that may allow recognition of these depositional settings in the stratigraphic record still remain unclear. Therefore, the Bakken Formation constitutes a unique opportunity to improve our understanding of the complexities associated with facies mosaics in this brackish-water marginal-marine setting.

## 1.5. REFERENCES


**Angulo, S.** and **Buatois, L. A.** (2009) Sedimentological and aspects of a sandy low-energy coast: Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-5, 17 p.

**Angulo, S.** and **Buatois, L. A.** (2010) Sedimentary facies distribution of the Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan: implications for understanding reservoir geometry, paleogeography, and depositional history. Summary of Investigations 2010, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2010-4.1, Paper A-4, 18 p.

**Angulo, S.** and **Buatois, L. A.** (2011) Petrophysical characterization of sedimentary facies from the Upper Devonian–Lower Mississippian Bakken Formation in the Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2011, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2011-4.1, 16 p.

**Angulo, S.** and **Buatois, L. A.** (2012) Ichnology of a Late Devonian–Early Carboniferous low-energy seaway: the Bakken Formation of subsurface Saskatchewan, Canada: Assessing paleoenvironmental controls and biotic responses. Palaegeography, Palaeoclimatology, Palaeoecology.

**Angulo, S.** and **Buatois, L. A.** (in press) Integrating depositional models, ichnology and sequence stratigraphy in reservoir characterization: the middle member of the Late Devonian–Early Carboniferous Bakken Formation of subsurface southeastern Saskatchewan revisited. American Association of Petroleum Geologists Bulletin.

**Angulo, S., Buatois, L. A.** and **Halabura S.** (2008) Paleoenvironmental and sequence-stratigraphic reinterpretation of the Upper Devonian–Lower Mississippian Bakken Formation of subsurface Saskatchewan: integrating sedimentological and ichnological data. Summary of Investigations 2008, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2008-4.1, CD-ROM, Paper A-3, 24 p.

**Bromley, R. G.** (1996) Trace fossils. Biology, Taphonomy and Applications, Second edition. Chapman and Hall, London, 361 p.

**Buatois, L. A.** and **Mángano, M. G.** (2011) Ichnology: Organism-Substrate Interactions in Space and Time. Cambridge University, 358 p.

**Christopher, J. E.** (1961) Transitional Devonian-Mississippian formations of southern Saskatchewan. Saskatchewan Department of Mineral Resources, Report 66, 103 p.

**Desjardins P. R., Buatois, L. A., Limarino C. O.** and **Cisterna, G. A.** (2009) Latest Carboniferous-earliest Permian transgressive deposits in the Paganzo Basin of western Argentina: lithofacies and sequence stratigraphy of a coastal plain to bay succession. Journal of South American Earth Sciences, 28, p. 40–53.

**Desjardins, P. R., Buatois, L. A., Mángano, M. G.** and **Limarino, C. O.** (2010) Ichnology of the latest Carboniferous-earliest Permian transgression in the Paganzo Basin of western Argentina: the interplay of ecology, sea-level rise, and paleogeography during postglacial times in Gondwana. Geological Society of America Special Paper 468, p.175–192.

**Geier, M.** and **Pemberton, S. G.** (1994) Ichnological and sedimentological aspects of the Ostracode Zone, Bellshill Lake-Killam area, east central Alberta, *in:* Pemberton S. G., James, D. P. and Wightman, D. M. (Eds.), Manville Core Conference. Canadian Society of Petroleum Geologists, Exploration Update, p. 315–330.

**Halabura, S. Buatois, L., Angulo, S.** and **Piché, L.** (2007) From Source to Trap: A Review of The Bakken Petroleum System, Upper Devonian–Mississippian, Southeast Saskatchewan; *in:* Summary of Investigations 2007, Volume 1, Saskatchewan Geological Survey, Saskatchewan Industry and Resources, Miscellaneous Report 20007-4.1, CD-ROM, Paper A-4, 8 p.

**Hayes, M. D.** (1985) Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota, in Mountain Geologist. Rocky Mountain Association of Geologists, Denver, Colorado, 22, p. 64–77.

**Hayes, B. J. R., Christopher, J. E. Rosenthal, L. Lus, G., McKercher, B., Minker, D., Tremblay Y. M.** and **Fennell, J.** (1994) The Manville Group, *in:* Mossop, D. G. and Shetsen, I. (Eds.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists, p. 317–334.

**Hubbard S. M., Pemberton, S. G.** and **Howard, E. A.** (1999) Regional geology and sedimentology of the basal Cretaceous Peace River Oil District. Bulletin of Canadian Petroleum Geology, 47, p. 270–297.

**Karma, R.** (1991) Geology and Geochemistry of the Bakken Formation (Devonian-Mississippian) in Saskatchewan. Master's thesis, University of Regina, 308 p.

**Kohlruss, D.** and **Nickel, E.** (2009) Facies analysis of the Upper Devonian–Lower Mississippian Bakken Formation, southeastern Saskatchewan. Summary of Investigations 2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-6, 11 p.

**Kreis, L. K. Costa, A.** and **Osadetz, K. G.** (2005) New perspectives on the hydrocarbon potential of Bakken and Torquay Formations, southeastern Saskatchewan, <http://www.cspg.org/conventions/abstracts/2005Core/kreis_l_hydrocarbon_potential_bakken_torquay.pdf> Accessed March 15th 2011.

**Kreis, L. K., Costa, A.** and **Osadetz, K. G.** (2006) Hydrocarbon potential of Bakken and Torquay formations, southeastern Saskatchewan, *in:* Gilboy, C. F., Whittaker, S. G. (Eds.), Saskatchewan and Northern Plains Oil & Gas Symposium 2006. Saskatchewan Geological Society Special Publication, 19, p. 118–137.

**LeFever, J. A., Martiniuk, C. D., Dancsok, E. F. R.** and **Mahnic, P. A.** (1991) Petroleum potential of the middle Member, Bakken Formation, Williston Basin, *in:* Christopher, J. E., Haidl, F. (Eds.), Sixth International Williston Basin Symposium. Saskatchewan Geological Society Special Publication, 11, p. 74–94.

**MacEachern, J. A., Zaitlin, B. A.** and **Pemberton, S. G. (**1999) A sharp-based sandstone of the Viking Formation, Joffre Field, Alberta, Canada: criteria for recognition of transgressively incised shoreface complexes. Journal of Sedimentary Research Section B, 69, p. 876–892.

**MacEachern, J. A.** and **Gingras, M.** (2007) Recognition of brackish-water trace-fossil suites in the Cretaceous Western Interior Seaway of Alberta, Canada, *in:* Bromley, R., Buatois, L. A., Mángano, M. G., Genise, J. Melchor, R. (Eds.), Sediment-Organism Interactions: A Multifaceted Ichnology. Society for Sedimentary Geology Special Publication, 88, p. 149–193.

**Mángano, M. G., Buatois, L. A., West, R.** and **Maples, C.** (2002) Ichnology of a Pennsylvanian equatorial tidal flat - the Stull Shale Member at Waverly, Eastern Kansas. Kansas Geological Survey Bulletin, 245, 133 p.

**McIlroy, D.** (2004) Some Ichnological concepts, methodologies, applications and frontiers, in McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geological Society of London Special Publication 228, p. 3–27.

**Pemberton, S. G., Spila, M., Pulham, A. J., Saunders, T., MacEachern, J. A., Robbins, D.** and **Sinclair, I. K.** (2001) Ichnology and sedimentology of shallow to marginal marine systems. Geological Association of Canada, Short Course Notes, 15. 343 p.

**Smith, M. G.** and **Bustin, R. M.** (1996) Lithofacies and paleoenvironments of the Upper Devonian and Lower Mississippian Bakken Formation, Williston Basin. Bulletin of Canadian Petroleum Geology, 44, p. 495–507.

**Smith, M. G.** and **Bustin, R. M.** (2000) Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, Western Canada Sedimentary Basin: a sequence stratigraphic interpretation. American Association of Petroleum Geologists Bulletin, 84, p. 940–960.

**Smith, M. G., Bustin, R. M.** and **Caplan, M. L.** (1995) Sequence stratigraphy of the Bakken and Exshaw formations: a continuum of black shale formations in the Western Canada Sedimentary Basin, *in:* Hunter, L. D. V., Schalla, R. A. (Eds.), 7th International Williston Basin Symposium. Montana Geological Society Special Publication, p. 399–409.

**Yoshida S., Johnson H. D., Pye K.** and **Dixon, R. J.** (2004) Transgressive changes from tidal estuarine to marine embayment depositional systems: The Lower Cretaceous Woburn Sands of southern England and comparison with Holocene analogs. American Association of Petroleum Geologists Bulletin.88, p. 1433–1460.

# 2. INTEGRATING DEPOSITIONAL MODELS, ICHNOLOGY AND SEQUENCE STRATIGRAPHY IN RESERVOIR CHARACTERIZATION: THE MIDDLE MEMBER OF THE DEVONIAN–CARBONIFEROUS BAKKEN FORMATION OF SUBSURFACE SOUTHEASTERN SASKATCHEWAN REVISITED


## Abstract

*The Upper Devonian–Lower Carboniferous Bakken Formation is a widespread siliciclastic unit in the subsurface of the Williston Basin that is subdivided into three members: lower and upper organic-rich shale members and a dolomitic silty and sandy middle member. Although in the last years the unit has become one of the most active oil plays in North America and numerous sedimentological studies have been made, no consensus about the depositional environments of the middle member has been achieved. Previous studies suggested a number of depositional and sequence-stratigraphic scenarios, including lowstand offshore-shoreface, normal-regressive offshore-shoreface, incised estuary, and falling-stage shoreface complexes for the middle member. In this paper, a new depositional and sequence-stratigraphic model is proposed, and compared with some previous interpretations. This new model includes a basal transgressive systems tract embracing shelf deposits, a highstand systems tract comprising shelf to lower shoreface environments, and an upper transgressive systems tract encompassing a brackish-water embayment complex and offshore to shelf settings. Petrophysical characterization of the sedimentary facies reveals that (i) bay-mouth cross-stratified fine-grained sandstone, (ii) flaser-bedded very fine-grained sandstone formed in wave-dominated tidal flats, (iii) offshore-transition highly bioturbated interbedded very fine-grained sandstone and siltstone, and (iv) tidal-flat very fine-grained sandstone with common mud drapes posses the best reservoir qualities. Recognition of a restricted embayment within the Bakken middle member has major implications for both exploration and production. Embayment facies with good reservoir quality constitute good oil prospects in localized areas, while fully marine facies may represent good oil prospects of more regional extent.*

## 2.1. INTRODUCTION

The Upper Devonian–Lower Carboniferous Bakken Formation constitutes a widespread siliciclastic unit in the subsurface of the Williston Basin in North Dakota, Montana, Manitoba, and Saskatchewan. In the last few years, it has become one of the most active oil plays in North America. In southeastern Saskatchewan, the number of wells drilled in the Bakken has dramatically increased in the last years [1737 producing wells were drilled between January 2005 and September 2010 (Kohlruss, 2011, written communication)]. In North Dakota and Montana, the U.S. Geological Survey has estimated technically recoverable undiscovered volumes of 3.65 billion barrels of oil, 1.85 trillion cubic feet of associated and dissolved natural gas, and 148 million barrels of natural gas liquids in the Bakken Formation (Pollastro et al., 2008).

During the early exploration of the Williston Basin, a persistent interval of black shale and siltstone was recognized underlying the Madison Group (LeFever et al., 1991). Different names (Kinderhook, Englewood, and Exshaw) were given to this interval (Fuller, 1956). Finally in 1953, the formal name of the Bakken Formation was adopted by the Williston Basin Correlation Committee (Ballard, 1963). Nordquist (1953) formally defined and described the Bakken Formation based on the well Amerada Petroleum Corporation–H.O. Bakken # 1 deep test (Sec. 12, T. 157 N., R. 95 W., Williams County) in North Dakota.

The Bakken Formation is subdivided into three members: lower and upper organic-rich black shale members, and a middle member of dolomitic siltstone and sandstone. Numerous studies have been carried out in this formation, including biostratigraphic, sedimentological and geochemical studies, and a variety of paleoenvironmental and sequence-stratigraphic models have been proposed (Fuller, 1956; Christopher, 1961; Smith and Bustin, 2000; Angulo et al., 2008; Angulo and Buatois 2009; Kohlruss and Nickel, 2009). Early depositional models suggested regressive swamps for the black shales of the lower and upper members, and transgressive-shallow marine deposits for the middle member (Fuller, 1956; McCabe, 1959; Christopher, 1961). However, the swamp interpretation was subsequently abandoned in favor of open-marine shelf settings for both the lower and the upper members (Lineback and Davidson, 1982; Webster, 1982; Karma, 1991; Smith and Bustin, 2000; Angulo et al., 2008, Angulo and

Buatois 2009; Kohlruss and Nickel, 2009). Nevertheless, a wide variety of depositional models has been proposed for the middle member, and no consensus has been achieved yet.

The aim of this chapter is to present a new depositional and sequence-stratigraphic model for the middle member of the Bakken Formation based on a detailed integrated sedimentological and ichnological analysis of cores. In this paper, the middle member is interpreted as having been formed in an offshore to shoreface environment during a normal regression followed by a transgressive brackish-water restricted embayment. We then compare this model with previous interpretations, such as lowstand offshore-shoreface complex (Smith and Bustin, 2000), normal-regressive offshore-shoreface complex and incised estuary (Angulo et al., 2008), and falling-stage shoreface complex (Kohlruss and Nickel, 2009) models. Finally, we discuss the implication of our model in reservoir characterization based on petrophysical evaluation and detailed isochore maps of the facies identified in the Bakken Formation.

## 2.2. METHODOLOGY

For this study, sixty-two cored wells from southeastern Saskatchewan were analyzed, integrating sedimentological and ichnological data. The study area covers approximately 29,900 $km^2$ (Townships 1 through 13, and Ranges 3 to 25 West of the Second Meridian) (Fig. 2.1). Cores were slabbed in order to provide a clear and detailed view of the facies. Outcrops of the partially coeval Exshaw Formation were studied in Jura Creek (type section) and Crowsnest Lake (roadcut on Highway 3), Alberta. Sedimentary facies were defined based on lithology, physical sedimentary structures, trace-fossil content and bioturbation index. For estimation of bioturbation index (BI), the Taylor and Goldring (1993) scheme was used. The environmental zonation for open-marine settings is based on MacEachern et al. (1999), in which the shelf is located below the storm-wave base, the offshore between the storm-wave base and the fair-weather wave base, and the shoreface between the low-tide line and the fair-weather wave base. For brackish-water bay deposits, the paleoenvironmental subdivision is based on the terminology of MacEachern and Gingras (2007), in which restricted bays are subdivided into distal-bay, bay-margin and bay-mouth deposits.

Isochore maps from each facies and subfacies were constructed for a better understanding of the spatial distribution of the sedimentary facies. For the sedimentary facies that are restricted

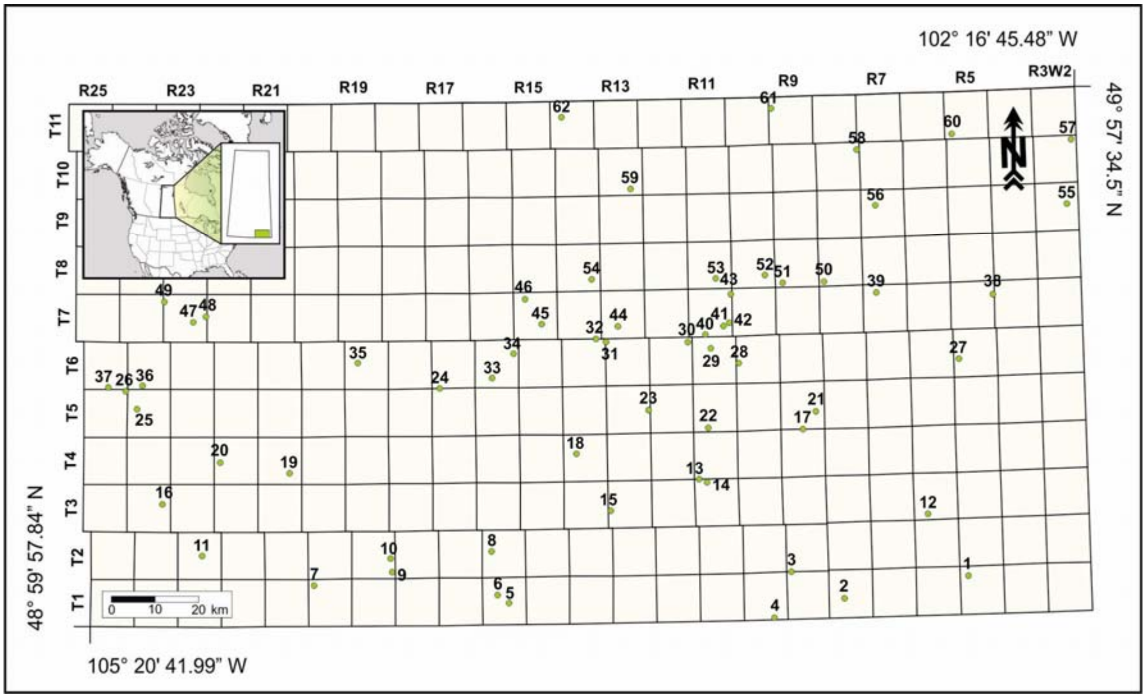



Figure 2.1 – Map of the study area showing well cores analyzed in this study (See Chapter 1 for well ID's).

to a specific stratigraphic intervals (e.g., facies 2, 4, and 5, subfacies 3A), isochore maps represent discrete occurrences. In contrast, for the sedimentary facies that recur vertically (e.g., subfacies 8A, 8B, facies 6, facies 9), isochore maps reflect the net thickness. However, two different isochore maps were made for facies 1, one for the lower member and another for the upper member. Maps were made using the software Surfer, version 8.08, with kriging as the gridding method.

In addition, core analyses from thirty-two logged well cores were used to characterize the porosity and permeability for each facies. For an accurate petrophysical characterization, plugs were carefully calibrated with the sedimentary facies, and once this calibration was made, values from each facies were grouped, and arithmetic mean for porosity and harmonic mean for permeability were calculated.

## 2.3. REGIONAL FRAMEWORK

The Bakken Formation is restricted to the subsurface of northeastern Montana, northwestern North Dakota, southeastern Saskatchewan and southwestern Manitoba. In Saskatchewan, it unconformably overlies the Big Valley in turn, is conformably overlain by the

Souris Valley Beds or the Lodgepole Formation (Christopher, 1961; LeFever et al., 1991; Kasper, 1995; Smith et al., 1995) (Fig. 2.2). Toward the west, in Alberta and British Columbia, it can be correlated with the Exshaw and Banff formations, and it is truncated to the north by the sub-Mesozoic unconformity in west-central Saskatchewan (Smith et al., 1995).

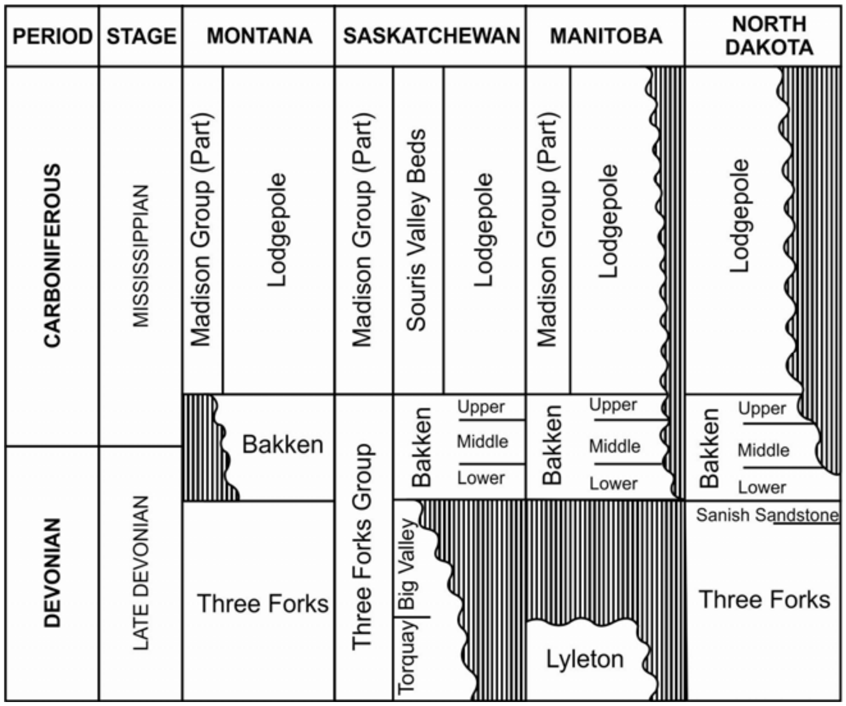



Figure 2.2 – Stratigraphic Chart for the Devonian–Carboniferous of Montana, Saskatchewan, Manitoba and North Dakota, showing the stratigraphy of the Bakken Formation within the Williston Basin (modified from Kasper, 1995).

The Bakken Formation is subdivided into three members: lower and upper organic-rich shale members, and a calcareous to dolomitic, sandy to silty middle member. These members are present throughout the subsurface of the Williston Basin, reaching their maximum thickness in North Dakota and thinning depositionally or erosionally to zero toward the north, south, and east margins of the basin. In wireline logs, the unit is easily recognizable due to the abnormally high gamma-ray readings (>200 API) of the lower and upper member shales (Meissner, 1978; Webster, 1982, 1984) and the normal wireline log characteristics for the siliciclastic and carbonates of the middle member (LeFever et al., 1991). The middle member has been subdivided informally by many authors. In this study, it has been subdivided into units A, B and C, while units A and B have been subdivided into subunits A1 and A2, and B1 and B2, respectively (Fig. 2.3).

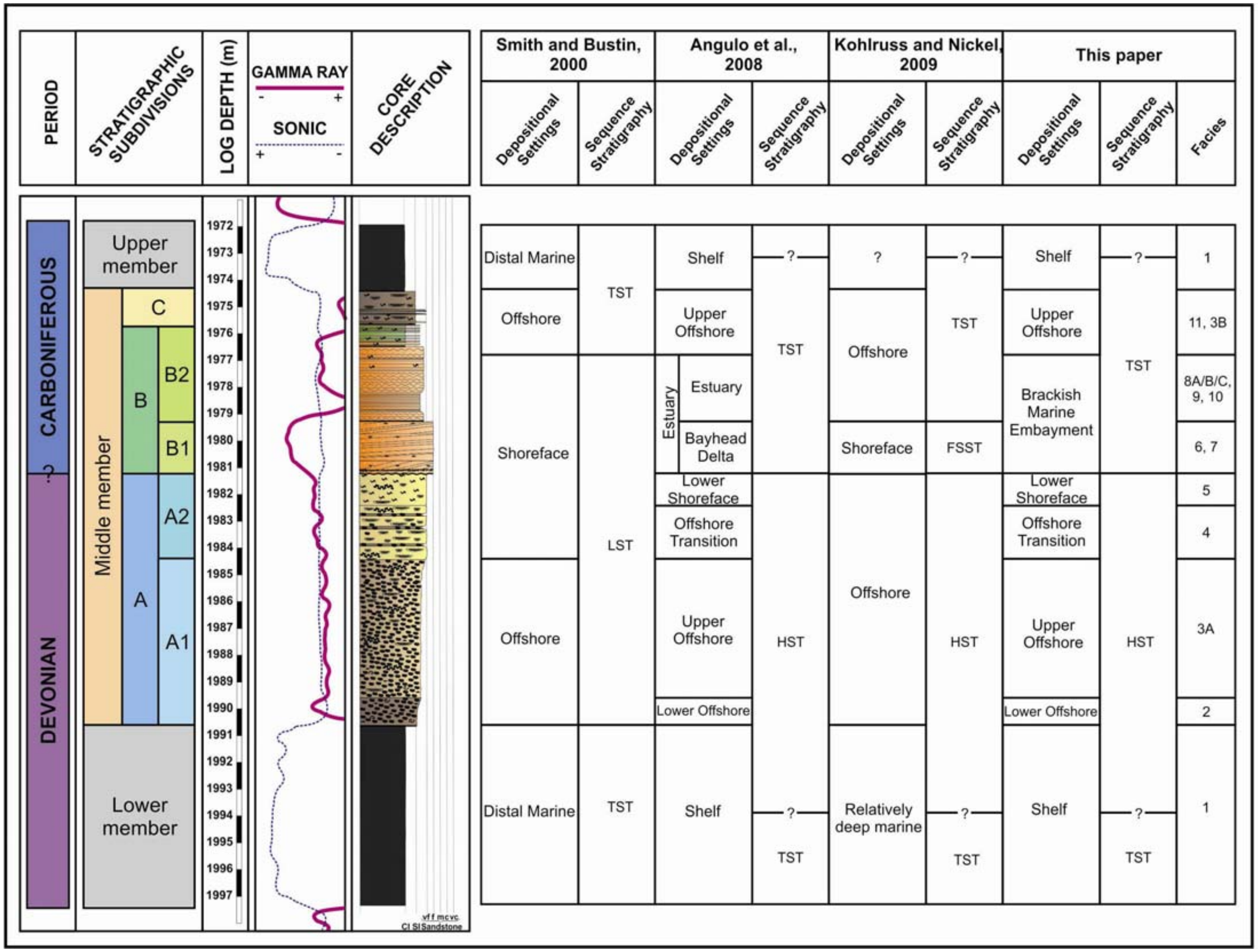



Figure 2.3 – Core log of the Bakken Formation (based on well core 15–31–3–11W2), showing its stratigraphic subdivisions, gamma ray and sonic wireline logs, and the different paleoenvironmental and sequence-stratigraphic models proposed for the Bakken Formation.

The Bakken Formation is Late Devonian–Early Carboniferous in age. Based on conodont biostratigraphy, Hayes (1985) and Karma (1991) assigned a Famennian age to the lower member and a Kinderhookian age to the upper member. The scarce recovery of conodonts between the shales of the lower and the upper member makes difficult the identification of the Late Devonian –Early Carboniferous boundary, but it is assumed to be within the middle member.

## 2.4. THE BAKKEN FORMATION REVISITED: A COMPLEX FACIES MOSAIC

### 2.4.1. Sedimentary Facies and Facies Associations

Eleven sedimentary facies, grouped into two facies associations (open marine and brackish-water marginal marine), were identified in cores of the Bakken Formation in southeastern Saskatchewan. The lower and upper members of the Bakken Formation consist of one facies (facies 1) characterized by mostly unbioturbated black shale, while the middle member is much more heterogeneous and includes a large variety of sedimentary facies (facies 2 to 11) (Table 2.1, Fig. 2.4).

Unlike previous interpretations that suggest open-marine conditions for the entire Bakken Formation (Smith et al., 1995; Smith and Bustin, 2000; Kohlruss and Nickel, 2009) (see, for an exception, Kasper, 1995), two facies associations have been recognized in this study: open marine and brackish-water marginal marine. Accordingly, the formation has been subdivided into three intervals: 1) a basal open-marine interval which comprises the lower black shale member and unit A from the middle member, 2) a middle brackish-water marginal-marine interval embracing unit B of the middle member, and 3) an upper open-marine interval which includes unit C of the middle member and the whole upper black shale member (Figs. 2.3, 2.5).

#### *2.4.1.1. Basal Open-Marine Interval*

The basal open-marine interval consists of a progradational succession, and comprises the lower member and unit A of the middle member. In ascending order, this interval consists of the shelfal black shale (facies 1), and lower-offshore calcareous muddy siltstone (facies 2), upper-offshore dolomitic sandy siltstone (subfacies 3A), and offshore-transition silty very fine-grained sandstone (facies 4). Locally lower-shoreface deposits occur at the top of the succession, and consist of interbedded massive very fine-grained sandstone with muddy partings and thinly

Table 2.1A - Sedimentological and ichnological characteristics of the sedimentary facies defined in southeastern Saskatchewan

| Facies | Lithology | Sedimentary Structures | Bioturbation Index | Ichnofossils | Sedimentary Environments |
|---|---|---|---|---|---|
| 1 | Black shale, pyrite and rare fragments of shells locally present | Massive, locally parallel lamination and injection cracks. | 0; locally 1 at the top | *Chondrites* isp. and *Thalassinoides* isp. *Zoophycos* isp. occurs in outcrops of the Exshaw Fm. | Shelf |
| 2 | Greenish gray, burrow-mottled, muddy siltstone, commonly calcareous, with fragments of brachiopod shells and crinoids | Massive with burrow mottled texture. | 5 to 6 | *Phycosiphon incertum*, burrow mottlings | Lower Offshore |
| 3A | Light gray or greenish gray, burrow-mottled, sandy siltstone to silty very fine-grained sandstone, commonly calcareous, pyritic, locally with brachiopod shell remains and discontinuous thin laminae of shale | Massive. Discrete beds are absent or extremely rare, but sandier and siltier zones are detected through the interval. Very rarely very thin parallel lamination occur in the sandier intervals. | 5 | Dominant ichnotaxa: *Phycosiphon incertum* and *Nereites missouriensis*. Subordinate ichnotaxa: *Asterosoma* isp., *Techichnus rectus*, and *Planolites montanus*. Rare element: *Rosselia* isp. | Upper Offshore (low intensity and frquency of storms) |
| 3B | Interbedded dark gray highly bioturbated siltstone and light gray, very fine-grained sandstone | Very thin lamination occur in the sandstones. Locally, wave ripples occur on top of the parallel-laminated beds. | Highly variable: in the siltstones 6; in the sandstones 0 to 1 | Dominant elements in the siltstones: *Phycosiphon incertum* and *Nereites missouriensis*. Dominant elements in the sandstones *Techichnus rectus*. Rare element: *Siphonichnus eccaensis* | Upper Offshore (moderate intensity and frquency of storms) |
| 4 | Interbedded light gray, massive, very fine-grained sandstone and siltstone. Deposits are generally slightly to moderate calcareous | Bed boundaries are diffused. Locally continuous shale laminae occur. | 4 to 5 | Dominant elements: *Nereites missouriensis*, and *Planolites montanus*. Subordinate ichnotaxa: *Phycosiphon incertum*, and *Asterosoma* isp. Rare element: *Rosselia* isp. | Offshore Transition |
| 5 | Interbedded light gray, massive, very fine-grained sandstone with muddy partings (< 1 mm) and thinly laminated very fine-grained sandstone | Massive with common intervals of wavy or parallel lamination. Continuous shale laminae occur. | Highly variable: in the maasive intervals 4 to 5; in the laminated intervals 0 to 1 | Dominant elements: *Planolites montanus*. Subordinate elements *Nereites missouriensis*, *Phycosiphon incertum*, and *Asterosoma* isp. | Lower Shoreface |

Table 2.1B- Sedimentological and ichnological characteristics of the sedimentary facies defined in southeastern Saskatchewan

| Facies | Lithology | Sedimentary Structures | Bioturbation Index | Ichnofossils | Sedimentary Environments |
|---|---|---|---|---|---|
| 6 | Light brownish gray, fine-grained sandstone, well sorted, calcareous, locally with oolites and pyrite | Erosive-based high-angle planar cross-stratified, some intervals are massive or present parallel lamination/low-angle cross-stratification. | 0 | None | Barrier Bar |
| 7 | Light gray, very fine-grained sandstone, well sorted, with mud drapes | Flaser bedded, with wave and current ripples, climbing ripples and mudstone drapes (1 mm to 8 cm thick) are also common. | 0 | None | Wave-Dominated Tidal Flat |
| 8A | Light to dark gray, beige and locally light red, commonly pyritic, in places slightly calcareous, very fine-grained sandstone | Wavy lamination, mudstone drapes, microfaults occur rarely. | 1 to 2 | *Planolites montanus* and burrow mottlings | Barrier Bar, Margin Bay |
| 8B | Light to dark gray very fine-grained sandstone, shale laminae are common; locally mud clasts occur (< 5mm) | Burrow mottled texture, irregular shale laminations, common soft deformation structures and rare microfaults occur. | 3 to 4 | Dominant elements: *Planolites montanus*, *Phycosiphon incertum*. Rare elements: *Nereites missouriensis* and *Teichichnus rectus* | Distal Bay |
| 8C | Light gray, very fine-grained sandstone with common shale laminae | Mudstone drapes are common (< 3 mm) and occur rhytmically, locally inclined heterolithic stratification and parallel lamination are also present. | 2 to 3 | *Planolites montanus* | Tidal Flat |
| 9 | Dark gray, very thinly interlaminated, very fine-grained sandstone and muddy siltstone, locally calcareous | Parallel lamination, locally current ripples cross-lamination and mudstone drapes. | 0 to 1 | *Planolites montanus* | Margin Bay |
| 10 | Very thinly interlaminated dark gray, mudstone and light gray, silty very fine-grained sandstone | Horizontal thin parallel lamination, locally mudstone drapes, syneresis cracks are also present, sandstone lenses and wave ripples occur. | 3 to 4 | Dominant ichnotaxa: *Planolites montanus* and *Teichichnus rectus*. Rare elements: *Thalassinoides* isp., *Rosselia* isp., and *Siphonichnus eccaensis* | Distal Bay |
| 11 | Sharp-based and poorly sorted coquina with sandy matrix | Massive with burrow mottled texture | 0 to 1 | Burrow mottling | High energy ravinement during drowning of the bay |


Figure 2.4 – Core photographs showing the sedimentary facies defined in the Bakken Formation in southeastern Saskatchewan.

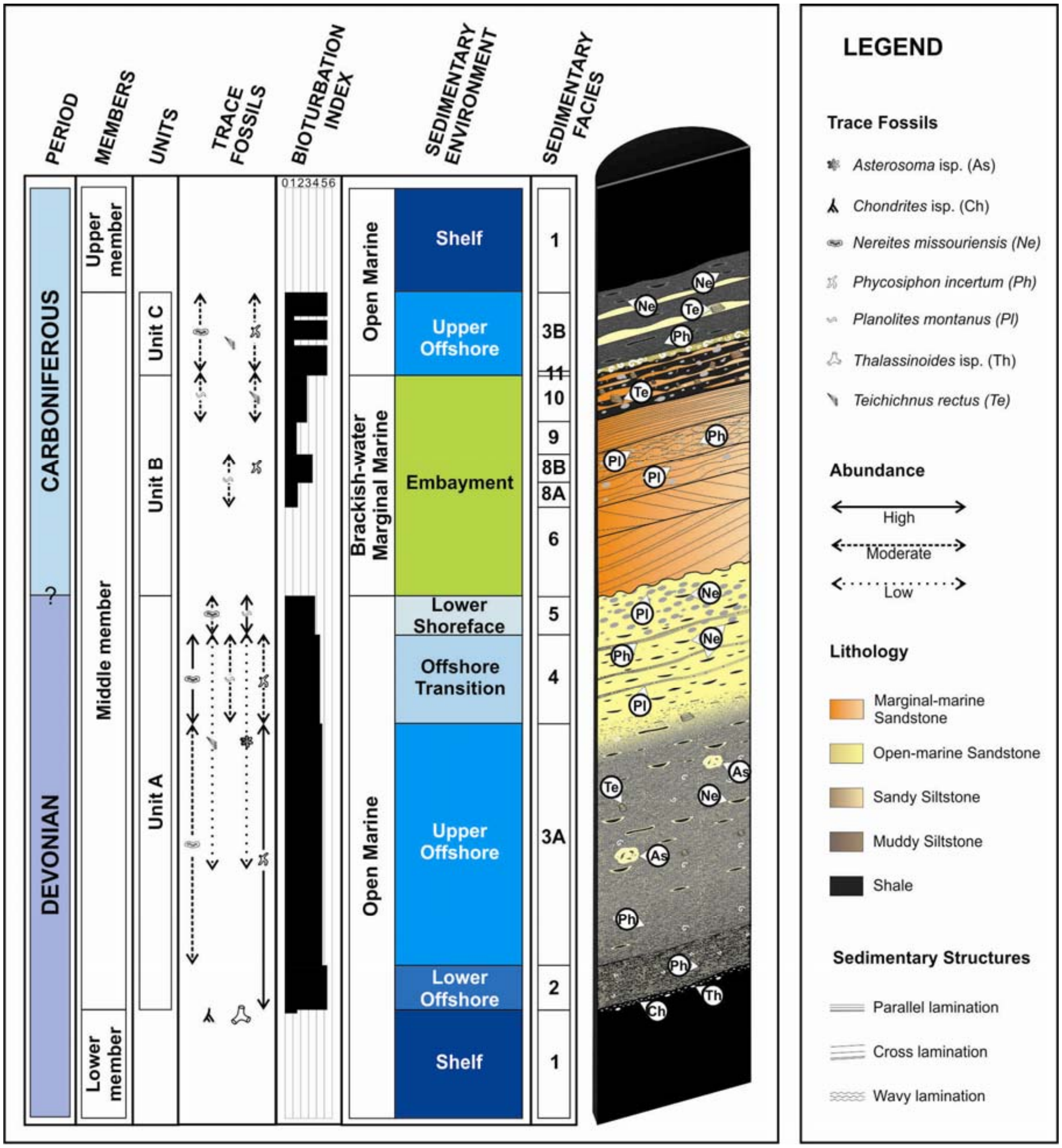



Figure 2.5 – Idealized core log displaying the sedimentological and ichnological characteristics of the Bakken Formation and the interpreted sedimentary environments. Facies 7 and subfacies 8C do not appear in the diagram, since very commonly where facies 6 is present, these facies are not. Average thickness of the Bakken Formation in southeastern Saskatchewan is about 23 m. Modified from Angulo and Buatois, 2009.

laminated very fine-grained sandstone (facies 5). The lack of discrete storm layers (tempestites) and primary sedimentary structures in these open-marine deposits is interpreted to be the result of intense bioturbation. However, the sand present in offshore and offshore-transition deposits is interpreted to have been carried out by storms below the fair-weather wave base. With the exception of the unconformable contact between the underlying Big Valley or Torquay formations and the Bakken lower member, and the sharp but conformable contact between the shelf and lower-offshore deposits (facies 1 and facies 2), facies contacts in the lower open-marine interval are gradational (Fig. 2.5). Except for the black shale of the lower member, where the lack of bioturbation suggests anoxic to dysoxic conditions, the open-marine intervals are characterized by a high bioturbation index and a "distal" *Cruziana* ichnofacies. Dominant elements are *Phycosiphon incertum* and *Nereites missouriensis*, while subordinate elements are *Planolites montanus*, *Asterosoma* isp., *Teichichnus rectus*, and rare elements are *Rosselia* isp., *Chondrites* isp., and *Thalassinoides* isp. (Figs. 2.6, 2.7). Although bioturbation is generally absent in the black shales from the lower and upper members, some cores revealed the presence of *Chondrites* isp. and *Thalassinoides* isp. near the top of the lower black shale, while *Zoophycos* isp. occurs in outcrops of the Exshaw Formation.

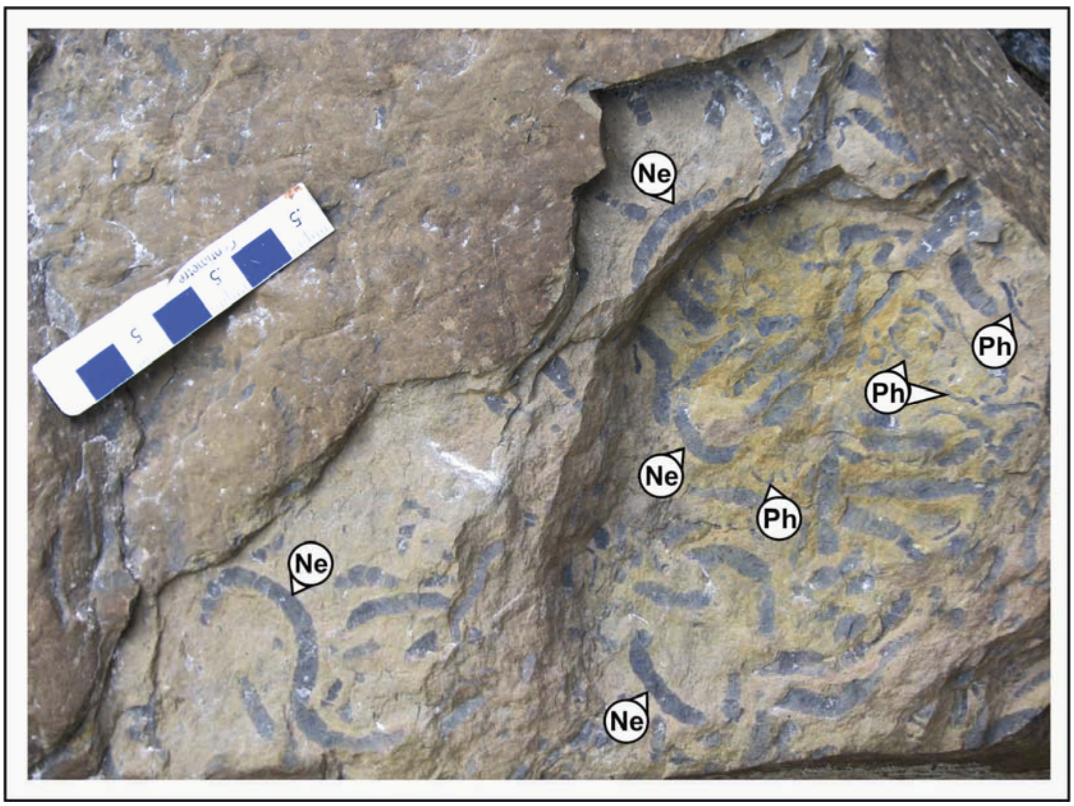



Figure 2.6 – Outcrop of the Exshaw Formation in its type section in Jura Creek, Alberta, showing an equivalent of subfacies 3A in the Bakken Formation. Note the presence of an identical trace-fossil assemblage, containing *Nereites missouriensis* (Ne) and *Phycosiphon incertum* (Ph).

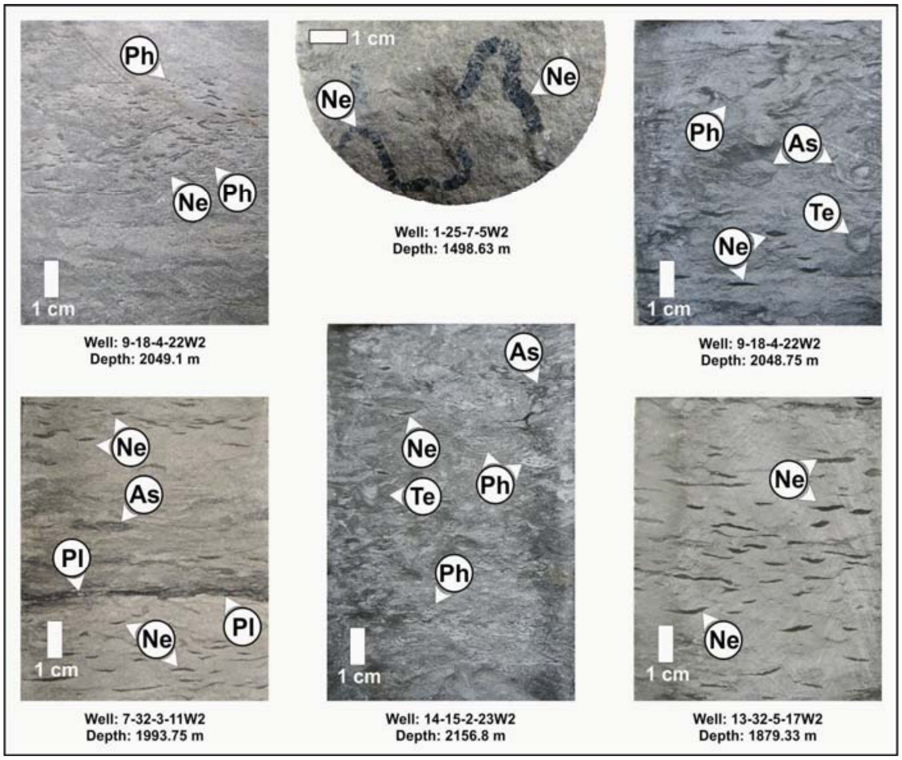



Figure 2.7 – Selected core intervals illustrating the “distal” *Cruziana* ichnofacies of the Bakken Formation. Elements include *Phycosiphon incertum* (Ph), *Nereites missouriensis* (Ne), *Teichichnus rectus*. (Te), *Asterosoma* isp. (As), and *Planolites montanus* (Pl). After Angulo and Buatois, 2009.

*2.4.1.2. Middle Brackish-Water Marginal-Marine Interval*

The lower open-marine interval is unconformably overlain by brackish-water marginal-marine deposits from unit B. These deposits are interpreted as having formed in a restricted bay, with limited or intermittent connection to the open sea. In the central region of the study area, cross-stratified fine-grained sandstone (facies 6) occurs at the base of the brackish-water marginal-marine deposits. This sandstone is interpreted as a northwest-southeast trending barrier bar that migrated toward the northeast as the transgression progressed. In the south-western region of the study area, only distal-bay deposits were preserved since previously formed barrier bars may have been eroded due to ravinement during the transgression. The contact between the brackish-water marginal-marine deposits and underlying open-marine deposits is sharp and erosive where the barrier-bar or wave-dominated tidal-flat deposits are present, and it is interpreted as an amalgamated sequence boundary and transgressive surface. On the other hand, in the regions where these deposits are not present, the contact is sharp (but without evidence of erosion). Barrier-bar deposits (facies 6 of subunit B1) pass upward into distal-bay deposits (subunit B2) comprising wavy-laminated very fine-grained sandstone (subfacies 8A), relatively highly bioturbated very fine-grained sandstone (subfacies 8B), thinly interlaminated siltstone, mudstone and very fine-grained sandstone (facies 9), and thinly interlaminated very fine-grained sandstone and mudstone (facies 10). In the southwest region of the study area, the base of the brackish-water interval consists of flaser-bedded very fine-grained sandstone (facies 7) and wavy-laminated very fine-grained sandstone with abundant mud drapes (subfacies 8C). These facies record deposition under strong tidal and wave influence in wave-dominated tidal flats (see Yang et al., 2008). Facies contacts within the brackish-water marginal-marine deposits are commonly gradational or sharp but conformable (Fig. 2.6). A major decrease in bioturbation index is recognized in unit B (bioturbation index 0 to 4, but commonly 0 to 2) with respect to that of the underlying open-marine facies (bioturbation index 5 to 6) (Figs. 2.6 and 2.8). The

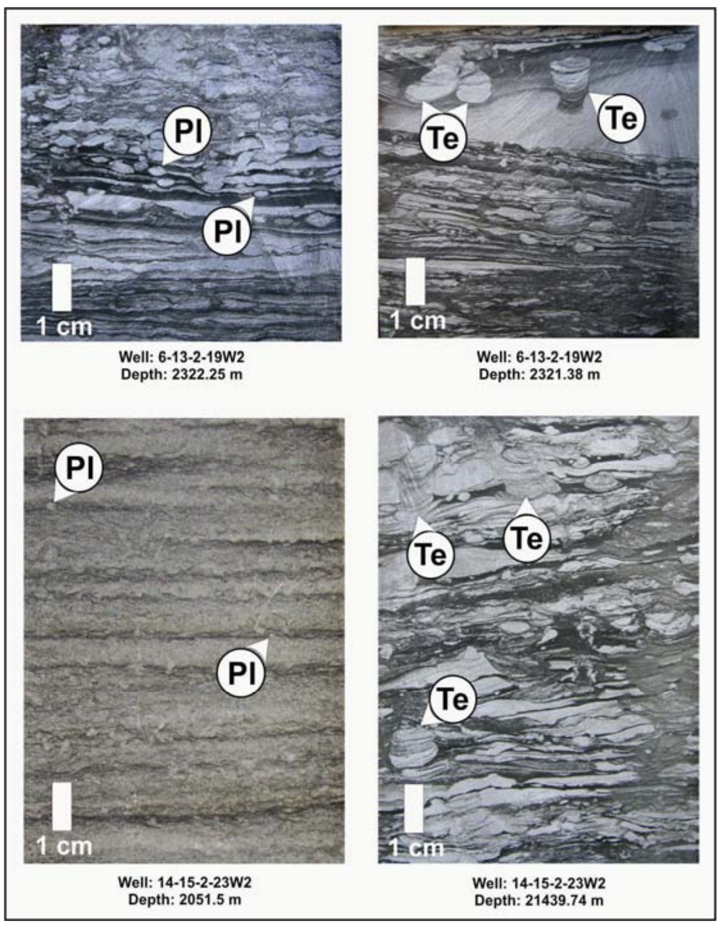



Figure 2.8 – Selected core intervals illustrating the “impoverished” Cruziana ichnofacies of the Bakken Formation. Elements include Teichichnus rectus (Te) and Planolites montanus (Pl).

trace-fossil association in these deposits is assigned to an "impoverished" *Cruziana* ichnofacies, in which dominant elements are *Planolites montanus* and *Teichichnus rectus*, while subordinate elements are *Rosselia* isp., *Thalassinoides* isp., and *Siphonichnus eccaensis*, and rare elements *Phicosiphon incertum* and *Nereites missouriensis* (Fig. 2.8) (Angulo et al., 2008; Angulo and Buatois, 2009, 2010). Brackish-water marginal-marine conditions are suggested by the small size of trace fossils, the low bioturbation index and reduced ichnodiversity, in addition to sedimentary structures that indicate tidal influence (e.g., mud drapes, flaser bedding), and syneresis cracks (which have been related to fluctuations in salinity; Foster et al., 1955; MacEachern and Pemberton, 1994).

*2.4.1.3. Upper Open-Marine Interval*

In the southeast region of the study area, a transgressive lag characterized by abundant fragments of shells (facies 11) overlies the brackish-water marginal-marine deposits, reflecting the initial re-establishment of fully-marine conditions. As the transgression continued, upper offshore interbedded siltstone and microhummocky cross-stratified very fine-grained sandstone (subfacies 3B from unit C of the middle member) accumulated over the entire study area, followed by the shelf black shale (facies 1) of the upper member. The contact between the previous embayment deposits and the upper open-marine interval is erosive where the transgressive lag is present and gradational when the latter is absent. The contact between the transgressive lag (facies 11) and the upper-offshore deposits (subfacies 3B) is gradational, while the contact between the upper-offshore (subfacies 3B) and the shelf deposits (facies 1) is sharp but conformable since no evidence of erosion or/and subaerial exposure has been detected (Fig. 2.6). The black shale of the upper member lacks bioturbation and the upper-offshore deposits from unit C are characterized by a "distal" *Cruziana* ichnofacies. *Phycosiphon incertum* and *Nereites missouriensis* are the dominant elements, and *Teichichnus rectus* and *Siphonichnus eccaensis* are rare elements (Fig. 2.7). In contrast with the upper-offshore deposits from the lower interval (unit A) in which tempestites were totally obliterated by biogenic reworking, storm beds have been preserved in the upper interval (unit C). This probably reflects higher frequencies and intensities of storm events, rather than different sedimentation rates (Angulo and Buatois, 2009).

### 2.4.2. Distribution of the Sedimentary Facies

Although localized salt dissolution and collapse of the underlying Middle Devonian Prairie Evaporite Formation has an important influence in the thickness of the Bakken Formation creating anomalously thickened zones, general trends can be noted in the sedimentary facies isochore maps. Isochore maps of the open-marine sedimentary facies show a wide distribution, covering the entire study with exception of lower-offshore deposits (facies 5) and the transgressive lag (facies 11). Isochore maps of lower-offshore (facies 2), upper-offshore (subfacies 3A) and offshore-transition deposits (facies 4) from the lower open-marine interval display a southwest-northeast trend, in which more distal facies (lower offshore) tend to be thicker in the southwest, whereas shallower-water facies (upper offshore and offshore transition) tend to thicken towards the northeast, reflecting a regular shoreline oriented northwest-southeast and located further northeast of the study area (Fig. 2.9). Lower-shoreface deposits are restricted to the south-southwestern region of the study area due to partial removal by subsequent erosion during sea-level fall. The transgressive lag occurs locally in the southeastern region of the study area.

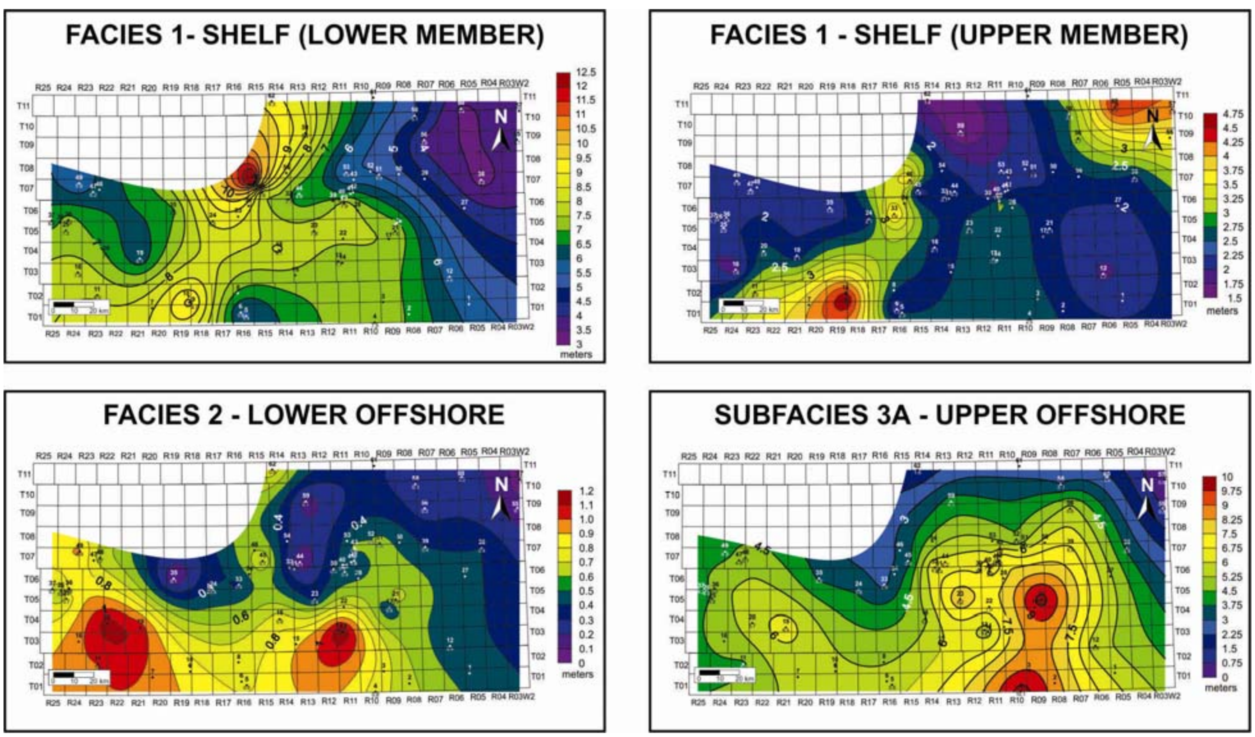



Figure 2.9A – Isochore maps of the open-marine sedimentary facies or subfacies. After Angulo and Buatois (2010).

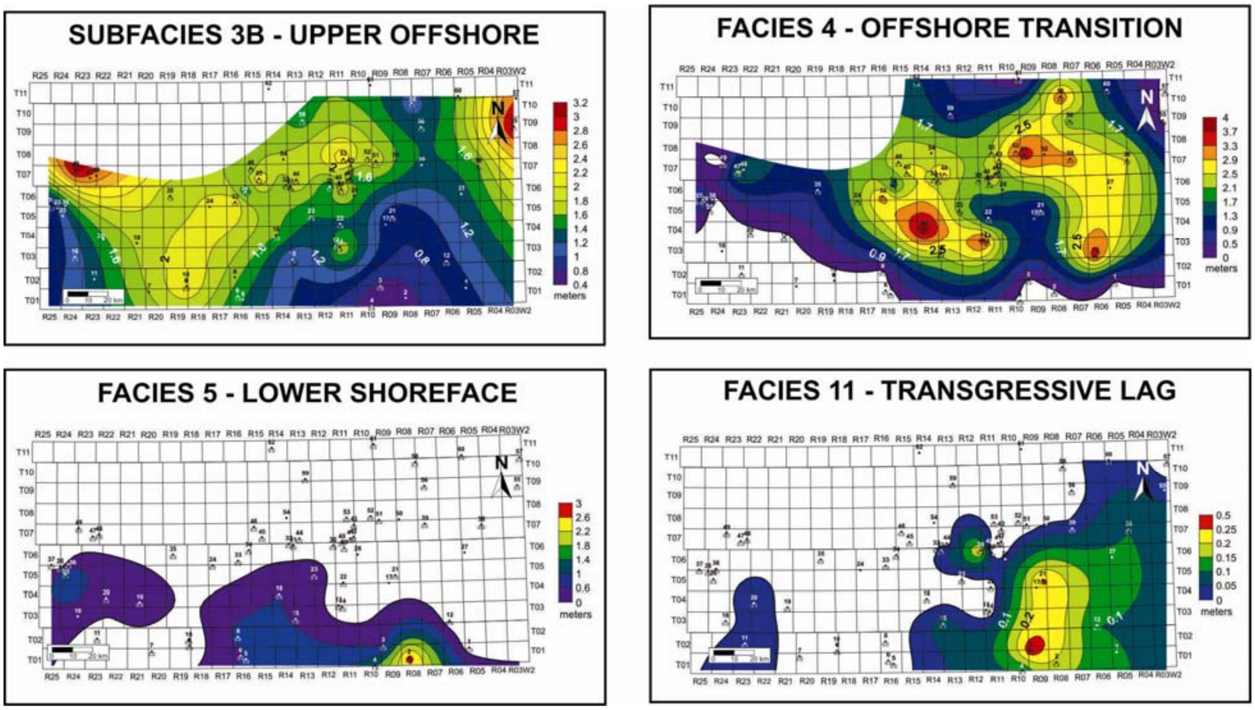



Figure 2.9B – Isochore maps of the open-marine sedimentary facies or subfacies. After Angulo and Buatois (2010)

Vertical stacking of the marginal-marine sedimentary facies and subsequent transgressive erosion as the embayment migrated from southwest to northeast resulted in a more heterogeneous and complex distribution for the brackish-water sedimentary facies than for that of the associated open-marine facies. Isochore maps of the marginal-marine interval show that some facies (6, 7 and subfacies 8C) are restricted to certain regions of the study area, while others (subfacies 8A, 8B, facies 9 and 10) are widely distributed, and no clear pattern is evident in the distribution of facies depocenters (Fig. 2.10) (Angulo and Buatois, 2010). In addition,

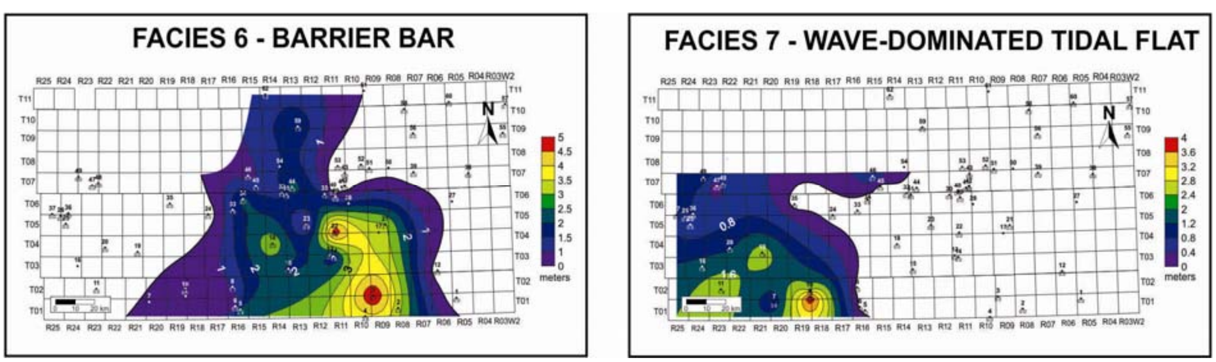



Figure 2.10A – Isochore maps of the brackish-water marginal-marine sedimentary facies or subfacies. After Angulo and Buatois (2010)

earlier barrier-bar deposits in the western region of the study area are not present since they might have been removed by erosion during the transgression, while earlier distal-bay deposits were preserved west of the barrier-bar deposits in the central region of the study area.

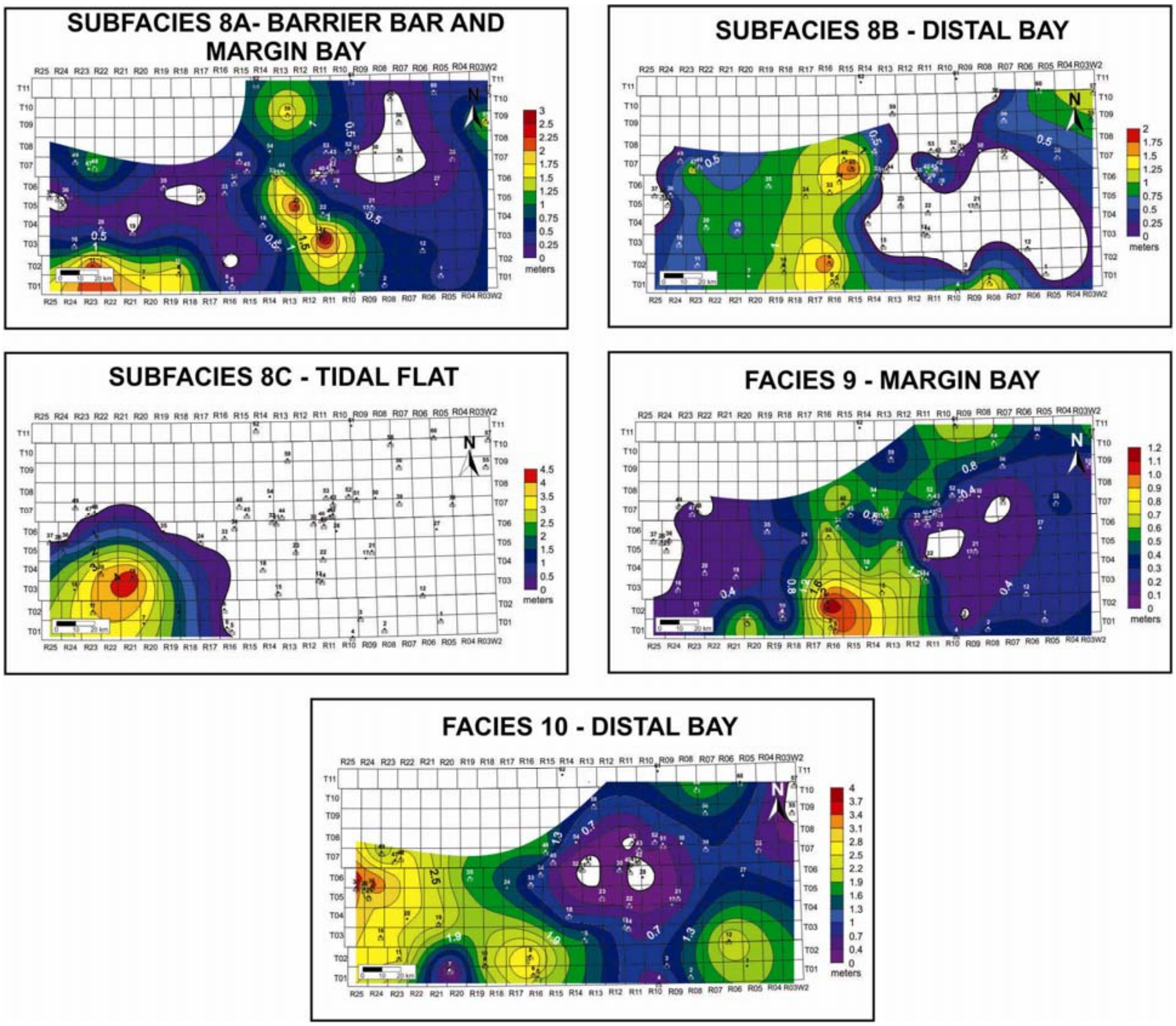



Figure 2.10B – Isochore maps of the brackish-water marginal-marine sedimentary facies or subfacies. After Angulo and Buatois (2010).

### 2.4.3. Sequence Stratigraphy

Three systems tracts are recognized in the Bakken Formation: a basal transgressive systems tract that comprises the lower interval of the lower member, a highstand systems tract embracing the upper interval of the lower member and unit A of the middle member, and an upper transgressive systems tract which encompasses unit B and C of the middle member, and the whole upper member (Figs. 2.3, 2.11, 2.12).

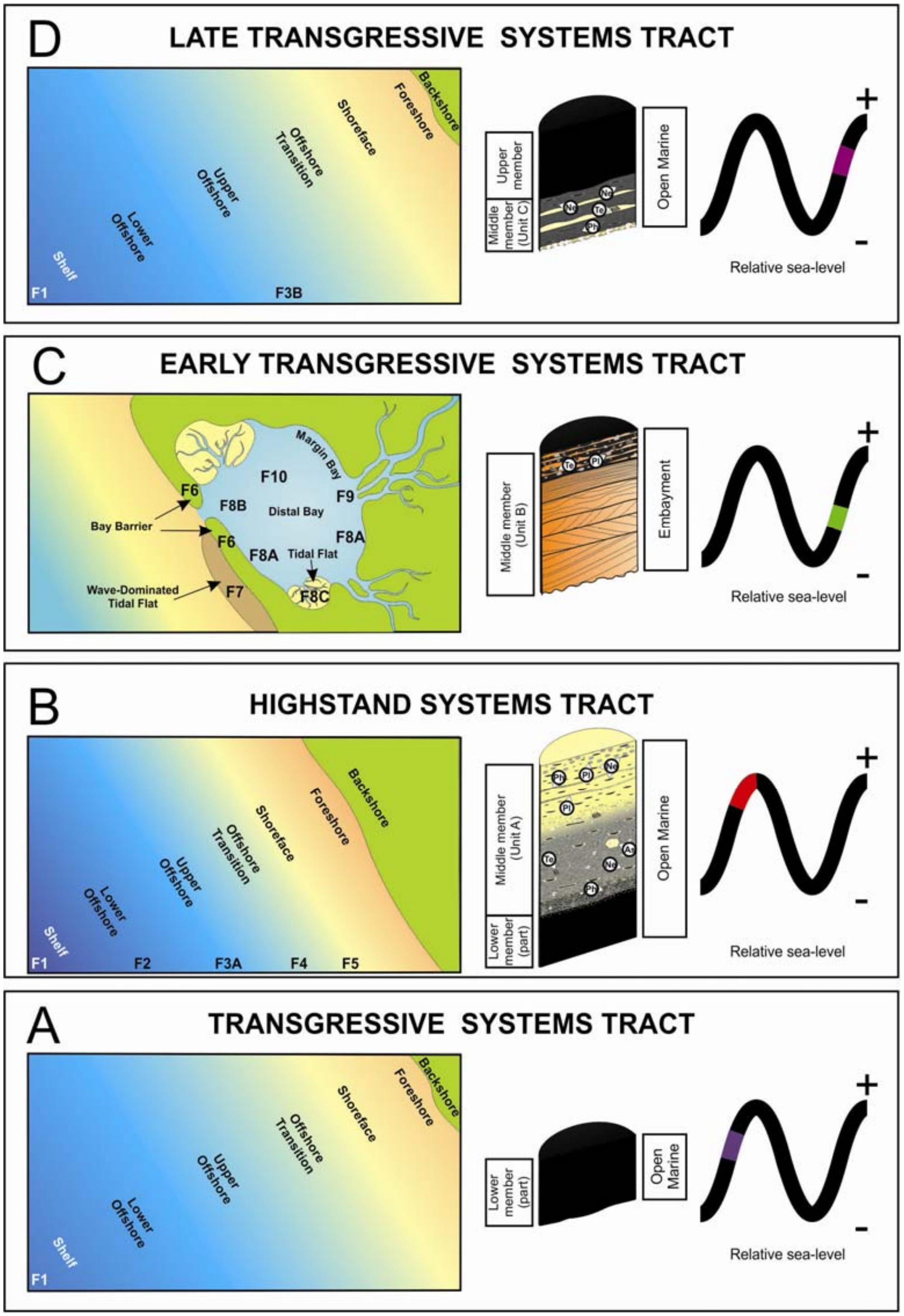



Figure 2.11 – Paleogeographic sketch illustrating the geological evolution of the Bakken Formation during transgressive (A), highstand (B), early transgressive (C), and late transgressive systems tracts (D).

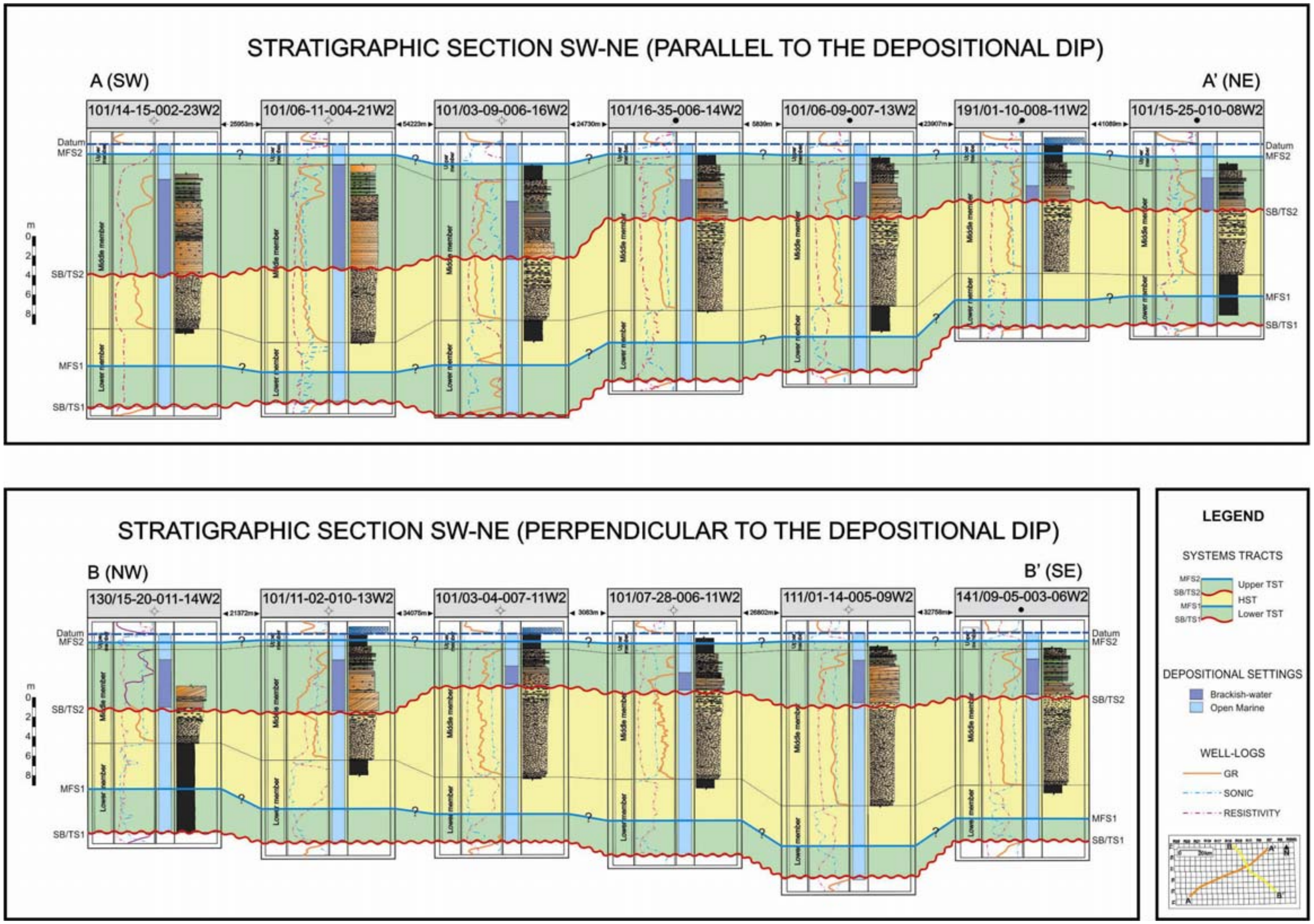



Figure 2.12 – Stratigraphic-cross sections showing the sequence-stratigraphic framework of the Bakken Formation parallel and perpendicular to depositional dip. The top of the Bakken Formation has been used as a stratigraphic datum. MFS are interpreted within the black shale of the lower and upper members. SB/TS1 is after Smith and Bustin (2000), while SB/TS2 is defined in this study. Note strong erosion associated with the sequence boundary within the middle member. (TST) Transgressive Systems Tract, (HST) Highstand Systems Tract, (SB) Sequence Boundary, (MFS) Maximum Flooding Surface, (TS) Transgressive Surface.

#### 2.4.3.1. *Basal Transgressive Systems Tract*

According to Smith and Bustin (2000), the Acadian unconformity was formed during the Late Devonian when a sea-level drop exposed most of the Williston Basin and eastern cratonic platform to erosion and reworking. In Saskatchewan this unconformity corresponds to the contact between the Big Valley or the Torquay and Bakken formations. Overlying the Acadian unconformity, the black shale of the lower member was deposited on a shelf below the storm wave base, mostly under anoxic conditions with some periods of dysoxia, and records the latest Devonian sea-level rise identified by Johnson et al. (1985). The black shale of the lower member typifies a condensed section with a very slow sediment accumulation over a broad area of the Western Canada sedimentary basin (Smith and Bustin, 2000). The basal contact is therefore considered a co-planar surface corresponding to a sequence boundary (Acadian unconformity) amalgamated with a transgressive surface (Angulo et al., 2008). The top of these transgressive deposits is marked by a maximum flooding surface within the black shale of the lower member (Figs. 2.11A, 2.12).

#### 2.4.3.2. *Highstand Systems Tract*

Following the transgression, the shoreline prograded towards the southwest into the shallow Devonian epicontinental sea. This package consist, from bottom to top, of shelfal black shale (lower member), and lower-offshore, upper-offshore and offshore-transition deposits (unit A of the middle member). Locally, lower-shoreface deposits occur at the top of the marine progradational succession. This progradational succession is interpreted as being deposited during a highstand systems tract (Figs. 2.11B, 2.12). Towards proximal positions (i.e., northeast of the study area), most if not all of the highstand systems tract deposits, have been removed by erosion due to a subsequent sea-level fall.

#### 2.4.3.3. *Upper Transgressive Systems Tract*

A drastic sea-level drop followed by a sea-level rise formed a brackish-water embayment with limited connection to the open sea, represented by unit B of the middle member. This embayment migrated southwest-northeast as the transgression proceeded. Therefore, earlier embayment deposits formed in the southwestern region of the study area were partially or totally removed during transgressive erosion. The contact with the previous highstand deposits (unit A) is interpreted as a sequence boundary (co-planar surface or amalgamated sequence boundary and transgressive surface) and possibly as the Devonian–Carboniferous boundary. This surface may represent the eustatic sea-level fall described by Sandberg et al. (2002) that resulted from the Devonian Southern Hemisphere glaciation (Figs. 2.11C, 2.12). The presence of a sequence boundary is indicated by a sharp and erosive contact between the underlying highstand deposits and the overlying transgressive deposits, and a facies jump between lower-shoreface deposits and brackish-water embayment marginal-marine deposits (Fig. 2.13).

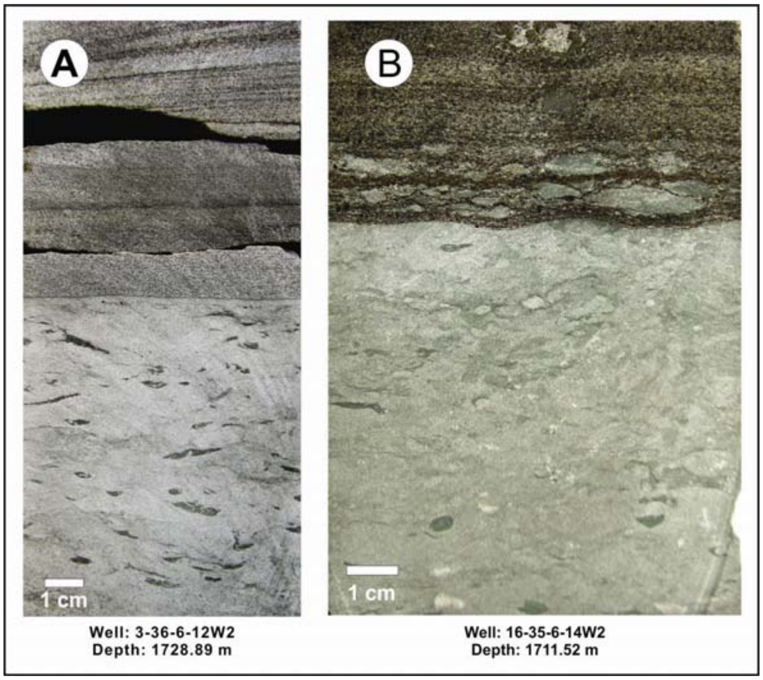



Figure 2.13 – Core photographs showing the sequence boundary between unit A and unit B of the middle member. (A) Sharp contact between intensely bioturbated open-marine offshore-transition deposits (facies 4) and non-bioturbated barrier-bar deposits (facies 6). (B). Erosive contact mantled by sandstone intraclasts from the underlying open-marine deposits, indicating that these were consolidated at the time of deposition of the barrier-bar unit, suggesting a hiatus between the two facies.

As the transgression proceeded, a transgressive lag was formed locally in the southeastern region of the study area. Finally, fully-marine conditions were re-established across the entire study area and upper-offshore deposits (unit C) and shelf deposits from the upper member accumulated during the late stage of the transgression. The top of this transgressive systems tract is marked by a maximum flooding surface within the black shale of the upper member (Figs. 2.11D, 2.12).

### 2.4.4. Petrophysical Characterization of the Sedimentary Facies

Three categories of reservoir rock quality were defined, based on the porosities and permeabilities in the different sedimentary facies of the Bakken middle member in the study area (Angulo and Buatois, 2011): (1) a poor-quality category characterized by permeabilities less than 0.08 md and porosities less than 5.6%, including facies 2, 9, and 10, as well as subfacies 3B, (2) a moderate quality category that has permeabilities which range between 0.04 to 0.09 md and porosities between 7.9 to 9.1%, and comprises facies 5, and subfacies 3A, 8A, and 8B, and (3) a good-quality category which is typified by permeabilities between 0.09 to 0.27 md and porosities between 8.6 to 12.0%, and comprises facies 4, 6 and 7, as well as subfacies 8C (Table 2.2, Fig. 2.14). Cross-plot charts of porosity versus permeability, and the number of wells and plug values used to characterize each sedimentary facies and subfacies, are shown in Appendix A.

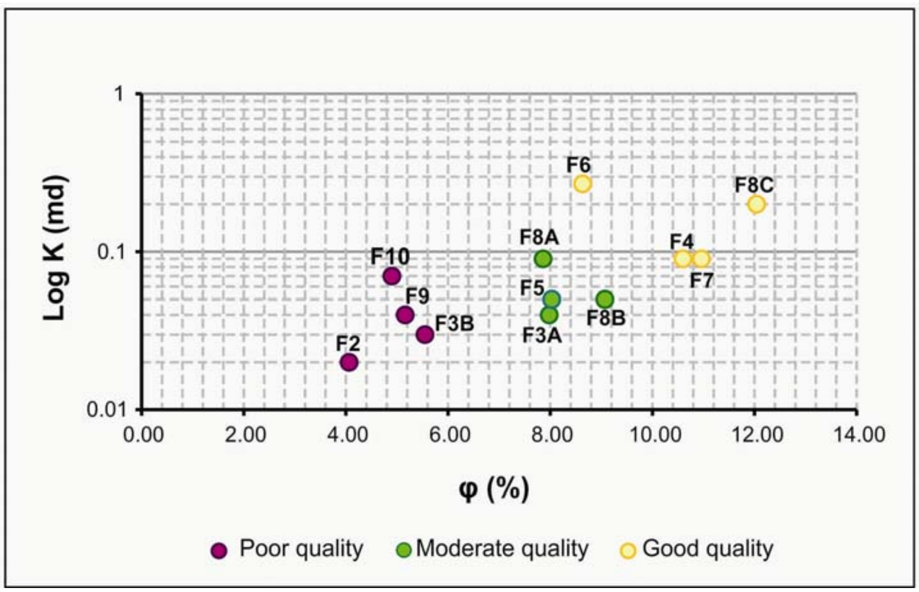



Figure 2.14 – Plot of Arithmetic mean porosity versus harmonic mean permeability for sedimentary facies of the Bakken middle member in southeastern Saskatchewan. After Angulo and Buatois, 2011.

Horizontal drilling and large sand-fracture completions are proving to be necessary strategies to obtain economic production from these low-permeability facies. Our results support previous work by Kreis et al. (2005), who mentioned that light-oil production in the Viewfield area is interpreted to come from the very fine-grained sandstone at the top of unit A2 of this study (facies 4), and that in some localities where the sandstones are less argillaceous and sedimentary structures such as flaser bedding are present (facies 7 of this study), the reservoir quality can be very good. Additionally, companies have regularly fractured and sometimes acidized facies 6, in an effort to enhance production.

Lithology plays the most important role in the rock quality of the sedimentary facies of the Bakken Formation. Poor-quality reservoir facies consist predominantly of fine-grained lithologies, and although these facies include very fine-grained sandstone, they are mostly dominated by siltstone and/or mudstone. Facies with moderate-quality reservoir rocks, although dominated by very fine-grained sandstone, still have a relatively high content of mud or silt. Finally, the facies with best reservoir rock quality include the sandiest and cleanest sandstones (very fine to fine-grained sandstone of facies 4, 6, 7 and subfacies 8C).

However, diagenesis also played a significant role in the petrophysical properties of the Bakken facies. The dominant, widespread cements in the middle member are dolomite, calcite, and pyrite, and their precipitation and dissolution influence porosity and permeability in the Bakken middle member (Ferdous, 2001). In subfacies 3A and facies 4, Kohlruss and Nickel (2009) reported the local presence of up to 70% dolomite as revealed by thin sections, suggesting that this unit is, in places, a silty dolostone, and therefore, their petrophysical properties are likely strongly controlled by diagenetic processes. In addition, facies 6, which was first targeted for exploration for being relatively free of argillaceous content and showing high resistivities in geophysical logs, is commonly calcite-cemented (Kreis et al., 2005). Therefore, although this facies is characterized by relatively good porosities and permeabilities, its petrophysical properties vary significantly both laterally and vertically within the facies [as is shown by the highest values of standard deviation of all the sedimentary facies (Table 2.2)], limiting its reservoir potential.

Bioturbation may have also played a key role in the petrophysical characteristics of the facies. Although the destruction of sediment porosity and permeability by bioturbation has been a dogma in reservoir characterization for many years, more recent studies have demonstrated that this is not always the case (e.g., Buatois et al., 1999; Gingras et al., 1999; Pemberton and Gingras, 2005; Tomkin et al., 2010). Selective feeding in *Nereites missouriensis* and *Phycosiphon incertum*, which are dominant elements in subfacies 3A and facies 4, may have played a key role in promoting light-oil transmissivity in low permeability reservoirs (Angulo and Buatois, 2011).

Table 2.2 – Petrophysical characteristics of the sedimentary facies of the Bakken Formation in southeastern Saskatchewan based on core analysis. Facies shaded in pink correspond to poor reservoir quality; green, moderate reservoir quality; yellow, good reservoir quality.

| Facies | Porosity (%) | | Permeability (mD) | | Core Analyzed | |
|---|---|---|---|---|---|---|
| | Arithmetic Mean | Standard Deviation | Harmonic Mean | Standard Deviation | # Wells | # Plugs |
| 1 | – | – | – | – | – | – |
| 2 | 4.1 | 1.7 | 0.02 | 0.08 | 4 | 8 |
| 3A | 8.0 | 3.0 | 0.04 | 0.17 | 25 | 217 |
| 3B | 5.5 | 2.6 | 0.03 | 0.27 | 7 | 19 |
| 4 | 10.6 | 2.2 | 0.09 | 0.63 | 17 | 108 |
| 5 | 8.0 | 1.9 | 0.05 | 0.1 | 5 | 15 |
| 6 | 8.6 | 3.3 | 0.27 | 5.34 | 12 | 107 |
| 7 | 11.0 | 2.8 | 0.09 | 1.14 | 4 | 31 |
| 8A | 7.9 | 2.2 | 0.09 | 1.82 | 15 | 43 |
| 8B | 9.1 | 2.0 | 0.05 | 0.11 | 7 | 21 |
| 8C | 12.0 | 1.8 | 0.2 | 0.15 | 5 | 8 |
| 9 | 5.2 | 3.0 | 0.04 | 0.08 | 8 | 15 |
| 10 | 4.9 | 2.7 | 0.07 | 0.08 | 2 | 18 |
| 11 | – | – | – | – | – | – |

## 2.5. COMPETING PALEOENVIRONMENTAL AND SEQUENCE-STRATIGRAPHIC MODELS FOR THE MIDDLE MEMBER OF THE BAKKEN FORMATION

### 2.5.1. Lowstand Offshore-Shoreface Complex of Smith and Bustin (2000)

Smith and Bustin (2000) interpreted the middle member to be an open-marine succession, in which units A1 and C were deposited in an offshore-marine setting, while subunit A2 and unit B reflect a continuum of lower-, middle- and upper-shoreface marine depositional settings. According to these authors, offshore deposits consist of alternating parallel bedded mudstone and burrow-mottled calcareous mudstone intervals. The burrow-mottled mudstones contain *in situ* brachiopod fragments and abundant trace fossils that were attributed to the *Nereites* ichnofacies. Shoreface deposits consist of thin sandstone beds with mudstone drapes, grading upward to flaser-bedded, trough cross-bedded and planar-cross-bedded sandstone. In this model, the upward change in physical sedimentary structures was reported to be accompanied by a transition from the *Cruziana* ichnofacies to the *Skolithos* ichnofacies.

Smith and Bustin (2000) recognized three systems tracts in the Bakken Formation: 1) a basal transgressive systems tract composed of the lower Bakken member, 2) a lowstand systems tract which includes unit A and B of the middle member, and 3) an upper transgressive systems tract that embraces subunit C of the middle member and the upper member (Fig. 2.3). The basal TST accumulated during the latest Devonian sea-level rise. The contact between the lower and the middle member was interpreted by Smith and Bustin (2000) as a sequence boundary. At this contact, they identified *Chondrites*, and regarded this ichnogenus as indicative of the *Glossifungites* ichnofacies. They concluded that the initial accumulation of lowstand deposits in the interior of the Williston Basin and the absence of basin-margin or channel-fill deposits contemporaneous with the middle member indicate a forced regression, and that relative sea-level drop was rapid. The offshore-shoreface lowstand deposits (unit A and B) constitute a shallowing-upward marine succession in which average grain size increases, sandstone beds thicken, and bioturbation intensity decrease from bottom to top as offshore mudstone (subunit A1) is superseded by lower-, middle- and upper-shoreface sandstone (subunit A2 and unit B). Finally, the offshore mudstone of unit C and the black shale of the upper member record the upper transgressive systems tract. In their scheme, the absence of a highstand systems tract on top of the lower member is explained invoking (1) little or no pause between sea-level rise and fall, or (2) erosion accompanying a rapid drop in sea level that removed evidence of deposition during sea-level highstand.

There are a number of factors that are unexplained by the lowstand offshore-shoreface complex interpretation for the middle member of the Bakken Formation:

1) According to Smith and Bustin (2000), offshore deposits (unit A and C) are characterized by the *Nereites* ichnofacies, while shoreface deposits (unit B) display a transition from the *Cruziana* to *Skolithos* ichnofacies. However, our detailed ichnological study indicates that the *Nereites* and *Skolithos* ichnofacies are not present in the Bakken deposits examined, and that the *Cruziana* ichnofacies is represented by its distal subdivision rather than its archetypal expression. Although the ichnospecies *Nereites missouriensis* (referred to as *Scalarituba* by Smith and Bustin, 2000) is one of the dominant elements in the offshore deposits, this ichnospecies is a facies-crossing form that has been recorded in both deep and shallow-marine deposits, and is a common component of the *Cruziana* ichnofacies (Mángano et al., 2002). Recognition of an ichnofacies is based on the trace-fossil assemblage and not by the presence of one ichnotaxon, even if it is the eponymous ichnogenus. The *Nereites* ichnofacies is typical of deep-marine turbidites, and it is characterized by the dominance of complex traps, farming structures and grazing trails produced by animals that have developed feeding strategies that allow them to cope with scarcity of food (Uchman, 2007). Sedimentological and ichnological evidence in unit A and B, which indicate a shallow-water (offshore) origin, would be difficult to reconcile

with deep-marine turbidites. *Nereites missouriensis* is associated with *Phycosiphon incertum*, *Asterosoma* isp., *Teichichnus* rectus., and *Rosselia* isp., which are deposit- or detritus-feeding structures. Overall, this assemblage is ascribed to the “distal” *Cruziana* (Pemberton et al., 2001; MacEachern et al., 2007; Buatois and Mángano, 2011). Finally, ichnofaunas dominated by vertical burrows of suspension feeders and passive predators are conspicuously absent in the studied cores of the Bakken Formation in southeastern Saskatchewan. Therefore, the presence of the *Skolithos* ichnofacies cannot be confirmed. The absence of ichnofaunas dominated by vertical burrows is consistent with deposition above storm wave base, but below fair-weather wave base, arguing against a shoreface setting.

2) Scarcity of bioturbation, low ichnodiversity, presence of an “impoverished” *Cruziana* ichnofacies and syneresis cracks in unit B cannot be explained by fully-marine conditions. The lack of sedimentary structures produced by wave action and the presence of sedimentary structures suggesting tidal influence (e.g., flaser bedding, mud drapes) do not support a shoreface interpretation for unit B.

3) The *Glossifungites* ichnofacies is characterized by sharp-walled, unlined, passively filled, dwelling burrows of suspension feeders or passive predators (Seilacher, 1967; MacEachern et al., 1992; Buatois and Mángano, 2011). *Chondrites* is a feeding structure produced either by deposit feeders or by chemosymbionts that actively filled their burrows (Seilacher, 1990; Fu, 1991; Bromley, 1996). Accordingly, the specimens of *Chondrites* at the top of the lower member cannot be interpreted as an evidence of the *Glossifungites* ichnofacies. Locally, the contact also contains compressed burrow systems attributed to *Thalassinoides* isp. Although *Thalassinoides* is a common component of the *Glossifungites* ichnofacies, the presence of compressed burrows indicates subsequent substrate compaction and emplacement in a softground rather than a firmground (Fig. 2.15). Therefore, there is no evidence to support the interpretation of the *Glossifungites* ichnofacies at the top of the black shale of the lower member.

4) The existence of an unconformity at the contact between the lower and middle member (unit A) is inconsistent with the sedimentological interpretation. Although the contact is rather sharp, no evidence of erosion, abrupt change in facies, or subaerial exposure

has been detected in southeastern Saskatchewan. Moreover, the unconformable contact between unit A and B, evidenced by the erosive nature and the drastic facies change, is not explained by this model.

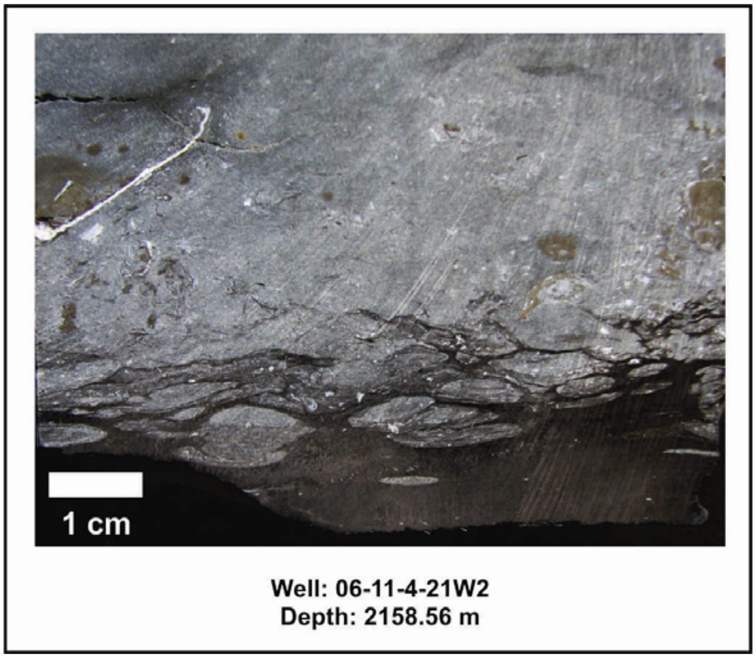



Figure 2.15 – Contact between the lower member (shelf deposits) and the middle member (lower-offshore deposits), in which compressed Thalassinoides isp. are observed, indicating that the mud was compressed after being bioturbated, which cannot be reconciled with a firmground *Glossifungites* ichnofacies.

### 2.5.2. Normal-Regressive Offshore-Shoreface Complex and Incised Estuary of Angulo et al. (2008)

According to Angulo et al. (2008), the middle Bakken was deposited in shallow-marine and estuarine settings. Siltstone and sandy siltstone from unit A1 and C were interpreted as lower- and upper-offshore deposits, while interbedded sandstone and siltstone and sandstone from subunit A2 are considered offshore-transition and lower-shoreface deposits, respectively. In this model, unit B was assumed to have formed in an estuarine setting as a response of a drastic sea-level drop and subsequent transgression. High-angle planar cross-stratified calcareous sandstone and wavy-bedded sandstone with mud drapes were interpreted as bayhead-delta deposits, while very thinly interlaminated sandstone and siltstone, and very thinly interlaminated, dark gray, mudstone and light gray, very fine-grained silty sandstone were considered as estuarine-basin deposits. On top of the estuarine deposits, a transgressive lag occurs locally in the southeastern region of the study area, marking the re-establishment of fully-marine conditions across the entire study area. Finally, upper-offshore (unit C) and shelf facies (upper member) were deposited.

The sequence stratigraphy of the Bakken Formation presented by Angulo et al. (2008) is very similar to the one presented in this paper. The same three systems tracts discussed in this paper are recognized in the normal-regressive offshore-shoreface complex and incised estuary model: lower TST, HST and upper TST.

This model is significantly different from that advanced by Smith and Bustin (2000) in many respects. The main differences are: (1) the recognition of brackish-water marginal-marine deposits in the middle member (unit B), in contrast with the fully-marine conditions interpreted for the entire Bakken Formation by Smith et al. (1995) and Smith and Bustin (2000); (2) the nature of the contact between the lower and the middle member [between shelf (facies 1) and lower-offshore deposits (facies 2)], which is considered as sharp but conformable instead of unconformable; and (3) the identification of an unconformity between fully marine deposits of unit A2 and brackish-water marginal-marine deposits of unit B1, which is considered as a conformable contact between offshore and shoreface deposits by Smith et al. (1995) and Smith and Bustin (2000).

Although the model proposed by Angulo et al. (2008) explains the brackish-water nature of the ichnofauna and the presence of tidal structures and syneresis cracks in the middle member, the distribution and geometry of the marginal-marine deposits seem to be inconsistent with deposition in an incised estuarine valley. According to quantitative data from the stratigraphic record (Reynolds, 1999; Gibling, 2006), the width of incised-valleys ranges between 500 m and 6.3 km, the thickness (depth) is from 2 to 152 m, and width-thickness ratio (W/T) is between 15 and 3000. Facies maps of the Bakken middle member (Angulo and Buatois, 2010) indicate that the marginal-marine facies belt is more than 60 km wide and less than 11 m thick, having a width/thickness ratio of 5454, which differs from incised-valley dimensions reported in the geological record.

Another inconsistency with an incised-valley interpretation is related to the orientation and the distribution of the fill. Most incised valleys can be divided into three zones from seaward to landward: an outer zone dominated by marine processes (estuary-mouth complex); a relative low-energy central zone, where marine energy is approximately balanced in the long term by river currents (central basin), and an inner river-dominated zone (bayhead delta) (Dalrymple et al., 1992). However, the distribution of the brackish-water marginal-marine facies in the middle member of the Bakken Formation does not show this tripartite zonation. Sediments interpreted as bayhead-delta deposits are extensively distributed in a northwest-southeast trend. Some of the facies interpreted as central basin deposits extend regionally covering the entire study area. Finally, estuary-mouth deposits were not recognized at all. However, the embayment model advocated in this paper would be consistent with the presence of older small incised valleys oriented perpendicular to the shoreline and formed during the sea-level fall. No evidence of these paleovalleys has been found to date.

### 2.5.3. Falling-Stage Shoreface Complex of Kohlruss and Nickel (2009)

Similar to Smith and Bustin (2000), Kohlruss and Nickel (2009) proposed offshore to shoreface settings for the Bakken middle member. They proposed that unit A reflects a shift from offshore-marine to shallow-marine settings, while unit B represents the proximal equivalent of unit A consisting of shoreface deposits (Fig. 2.3).

Kohlruss and Nickel (2009) recognized four systems tracts within the Bakken Formation: a basal transgressive systems tract which comprises the lower portion of the lower member; a highstand systems tract embracing the upper portion of the lower member and unit A of the middle member; a falling stage systems tract and a lowstand systems tract encompassing unit B; and an upper transgressive systems tract which comprises unit C and the upper member. The basal transgressive systems tract accumulated in relatively deep water under a very slow sedimentation rate. As the rate of sea-level rise decreased, progradation of the shoreline occurred and the upper portion of the lower member and unit A were deposited in a highstand systems tract, which is bounded at the top by a regressive surface of marine erosion that marks the beginning of the falling stage systems tract. In this model, falling sea level was characterized by sediment bypass and accumulation of sediment in paleogeographic lows. Lowstand deposits were identified by Kohlruss and Nickel (2009) by aggradation of unit B surrounding the margins of the Viewfield region of Saskatchewan. According to these authors, aggradation was the result of the continuing progradation of the shoreface, but at a diminished rate which allowed sediment to build up. During relative sea-level rise, a basal transgressive shell lag developed, and unit C onlapped the underlying deposits and covered the entire study area. The upper member shale represents the final stage of transgression and the following relative sea-level highstand.

In contrast to Smith and Bustin (2000) and in agreement with Angulo et al. (2008), the model proposed by Kohlruss and Nickel (2009) regarded the contact between the lower and middle members (unit A) as gradational and the corresponding succession as resulting from a normal regression. Also, this model agrees with that of Angulo et al. (2008) and the new model presented in this paper in considering the contact between units A and B as sharp and unconformable. However, a major departure is the interpretation of unit B1 as a falling-stage shoreface and the lowermost part of unit B2 as offshore deposits. The main problem with this interpretation is that the low degree of bioturbation, the low ichnodiversity, and the "impoverished" *Cruziana* ichnofacies which characterize most of unit B cannot be explained under open-marine conditions. Shoreface-offshore deposits are typified by the *Cruziana* and *Skolithos* ichnofacies, high levels of bioturbation and high ichnodiversity, which cannot be confirmed in unit B. In addition, these deposits display abundant syneresis cracks and sedimentary structures that imply tidal influence, such as mud drapes and flaser bedding, rather than sedimentary structures indicative of oscillatory flows as would be expected in a wave-dominated offshore-shoreface complex. However, because of by-pass linked to falling sea level, it is suggested in this paper that forced-regressive shoreface deposits may be present in a more distal position (i.e., towards the southwest) beyond the study area.

## 2.6. IMPLICATIONS OF THE NEW MODEL IN RESERVOIR CHARACTERIZATION

The new sedimentological model proposed in this paper better explains the sedimentological and ichnological features recorded in the Bakken Formation, and therefore represents a more robust interpretation of the geological evolution and the environmental settings that prevailed during deposition of the unit. The spatial distribution of the facies and their reservoir quality are strongly controlled by physical, chemical and biological conditions during deposition. Therefore, a better understanding of the depositional conditions and reservoir architecture allows a more accurate prediction and delineation of prospective sedimentary facies. In southeastern Saskatchewan, for example, open-marine facies show a fairly regional distribution when compared with the brackish-water marginal-marine facies. In addition, marginal-marine embayment deposits commonly interfinger to form much more compartmentalized reservoirs, in contrast with the open-marine facies which are laterally persistent forming facies belts parallel to depositional strike. Evaluation of potential reservoir rock should take into consideration not only petrophysical properties, but also distribution of the sedimentary facies. Within facies group 3 (best reservoir quality), facies 4 (offshore transition) has the best reservoir potential due to its fairly regional distribution in the study area and its thickness, which reaches a maximum of 4 m in the central-northeast region of the study area. This is in sharp contrast with subfacies 8C, and facies 7 and 6, which are much more restricted and/or thinner. However, the latter ones can locally constitute good reservoirs. Potentially, areas with good reservoir characteristics in remnant barrier-bar and tidal deposits (facies 6, 7, and subfacies 8C) could remain undiscovered, left by incomplete erosion during the northeastward migration of the embayment.

## 2.7. CONCLUSIONS

Integration of ichnological and sedimentological data in the Bakken Formation allowed the identification not only of open-marine conditions as suggested by some previous interpretations, but also brackish-water marginal-marine conditions in southeastern Saskatchewan. Low bioturbation degree, low ichnodiversity, and an "impoverished" *Cruziana* ichnofacies, together with sedimentary structures suggestive of tidal influence (e.g., flaser bedding, mud drapes) and salinity changes (i.e., syneresis cracks), and the spatial distribution of the sedimentary facies all provide evidence for the establishment of a brackish-water embayment during deposition of unit B.

Recognition of marginal-marine deposits in the Bakken has a great impact in the understanding of the geological evolution of the unit and its sequence-stratigraphic framework. Neither the lowstand offshore-shoreface complex of Smith and Bustin (2000), nor the falling-stage shoreface complex of Kohlruss and Nickel (2009) explain the evidence of brackish-water conditions in unit B. On the other hand, although the offshore-shoreface complex and incised estuary model proposed by Angulo et al. (2008) would explain the ichnological characteristics and some of the sedimentological features of unit B, the distribution and geometry of the marginal-marine deposits is inconsistent with estuarine deposition. Accordingly, the embayment model is proposed here to reconcile all the available lines of evidence.

According to the petrophysical characterization of the sedimentary facies of the Bakken Formation, facies 6, 7, 4 and subfacies 8C have the best rock quality with the highest porosities (8.6% to 12%) and permeabilities (0.09 md to 0.27 md).

Although different parameters, such as lithology, diagenesis and bioturbation, played a key control on the reservoir quality of the rock, the importance of spatial distribution of the sedimentary facies in reservoir potential should not be overlooked. Of the facies with the best reservoir qualities (group 3), facies 4 was the only one deposited within an open-marine realm and characterized by a broad distribution and relatively thick interval. Therefore, facies 4 seems to have the best reservoir potential in southeastern Saskatchewan, while facies 6 and 7, and subfacies 8C locally constitute good targets.

## 2.8. ACKNOWLEDGMENTS

The authors thank Saskatchewan Energy and Resources and the University of Saskatchewan for providing financial support for this project. Additional funds were provided by AAPG (Grants 2008, 2009), IAS (Grant 2009) and Shell Canada. We would like to give special thanks to the Geological Subsurface Laboratory staff in Regina, particularly to Melinda Yurkowski, Chris Gilboy, Erik Nickel, Dan Kohlruss, Chao Yang, Tyler Music, and all the technical team that diligently displayed the cores for this study; without their support this project would have not been possible. We are also grateful to Robin Renaut for critically reading this manuscript. This project benefited from constructive discussion with Gabriela Mángano, Kim Kreis, John Lake, Andrew Nimegeers, Carol Brown, Fran Haidl, and Brian Pratt. We also want to thank the Londoño family for providing free accommodation and all their support during core work in Regina. Reviews by Kent Bowker, Ashton Embry and David Morse, and editorial comments by Stephen Laubach and Frances Whitehurst are greatly appreciated.

## 2.9. REFERENCES

**Angulo, S.** and **Buatois, L. A.** (2009) Sedimentological and aspects of a sandy low-energy coast: Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-5, 17 p.

**Angulo, S.** and **Buatois, L. A.** (2010) Sedimentary facies distribution of the Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan: implications for understanding reservoir geometry, paleogeography, and depositional history. Summary of Investigations 2010, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2010-4.1, Paper A-4, 18 p.

**Angulo, S.** and **Buatois, L. A.** (2011) Petrophysical characterization of sedimentary facies from the Upper Devonian–Lower Mississippian Bakken Formation in the Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2011, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2011-4.1, 16 p.

**Angulo, S., Buatois, L. A.** and **Halabura S.** (2008) Paleoenvironmental and sequence-stratigraphic reinterpretation of the Upper Devonian–Lower Mississippian Bakken Formation of subsurface Saskatchewan: integrating sedimentological and ichnological data. Summary of Investigations 2008, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2008-4.1, CD-ROM, Paper A-3, 24 p.

**Ballard, F. V. (1963) Structural and stratigraphic relationship in the Paleozoic rocks of eastern North Dakota. North Dakota Geological Survey, Bulletin 40, 42 p.**

**Bromley, R. G.** (1996) Trace fossils. Biology, taphonomy and applications. Chapman and Hall, London, 361 p.

**Buatois, L. A., Mángano, M. G.** and **Carr, T. R.** (1999) Sedimentology and ichnology of Paleozoic estuarine and shoreface reservoirs, Morrow Sandstone, Lower Pennsylvanian of Southwest Kansas, USA. Current Research in Earth Sciences 241, p. 1–27.

**Buatois, L. A.** and **Mángano, M. G.** (2011) Ichnology: Organism-substrate interactions in space and time. Cambridge University Press, 358 p.

**Christopher, J. E.** (1961) Transitional Devonian–Mississippian formations of southern Saskatchewan. Saskatchewan Department of Mineral Resources Report 66, 103 p.

**Dalrymple, R.W., Zaitlin, B. A.** and **Boyd, R.** (1992) Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology, v. 62, p. 1130–1146.

**Ferdous, H. (**2001) Regional sedimentology and diagenesis of the middle Bakken member: implications for reservoir rock distribution in southern Saskatchewan. University of Saskatchewan, PhD thesis, Electronic Thesis and Dissertations, 392 p.

**Foster, W. R.**, **Savins, J. G.** and **Waite, J.M.** (1955) Lattice expansion and rheological behaviour relationships in water-montmorillonite systems. Proceedings Third National Conference on Clays and Clay Minerals. National Academy of Sciences, Natural. Resources Council Publication 395, p. 296–316.

**Fu, S.** (1991) Funktion, Verhalten und Einteilung fucoider und lophocteniider Lebensspuren. Courier Forschunginstitut Senckenberg, 135, p. 1–79.

**Fuller, J. G. C. M.** (1956) Mississippian rocks and oilfields in southeastern Saskatchewan, Regina, Saskatchewan. Department of Mineral Resources Report 19, 72 p.

**Gibling, M. R.** (2006) Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. Journal of Sedimentary Research, 76, p. 731–770.

**Gingras, M. K., Pemberton, S. G., Mendoza C. A. and Henk F. (1999)** Assessing the anisotropic permeability of *Glossifungites* surfaces. *Petroleum Geoscience*, 5, p. 349–357.

**Hayes, M. D.** (1985) Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota, in Mountain Geologist. Rocky Mountain Association of Geologists, Denver, Colorado, 22, p. 64–77.

**Johnson J. G.**, **Klapper, G.** and **Sandberg, C. A.** (1985) Devonian eustatic fluctuations in Euroamerica. Geological Society of America Bulletin, 96, p. 567–587.

**Karma, R.** (1991) Geology and Geochemistry of the Bakken Formation (Devonian-Mississippian) in Saskatchewan. Master's thesis, University of Regina, 308 p.

**Kasper, D. L.** (1995) Aspects of the sedimentology, stratigraphy, and diagenesis of the Upper Devonian-Lower Mississippian Bakken Formation of west-central Saskatchewan. Master's thesis, University of Saskatchewan, 294 p.

**Kohlruss, D.** and **Nickel, E.** (2009) Facies analysis of the Upper Devonian – Lower Mississippian Bakken Formation, southeastern Saskatchewan. Summary of Investigations

2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-6, 11 p.

**Kreis, L. K. Costa, A.** and **Osadetz, K. G.** (2005) New perspectives on the hydrocarbon potential of Bakken and Torquay Formations, southeastern Saskatchewan, <http://www.cspg.org/conventions/abstracts/2005Core/kreis_l_hydrocarbon_potential_bakken_torquay.pdf> Accessed March 15th 2011.

**LeFever, J. A., Martiniuk, C. D., Dancsok, E. F. R.** and **Mahnic, P. A.** (1991) Petroleum potential of the middle Member, Bakken Formation, Williston Basin, *in* J. E., Christopher, and F., Haidl (Eds.), Sixth International Williston Basin Symposium. Saskatchewan Geological Society Special Publication 11, p. 74–94.

**Lineback, J. A.** and **Davidson M. L.** (1982) The Williston Basin - sediment starved during the Early Mississippian, *in* J. E., Christopher, and J. Kaldi (Eds.), 4th International Williston Basin Symposium. Saskatchewan Geological Society Special Publication 6, p. 125–130.

**MacEachern, J. A.** and **Pemberton, S. G.** (1994) Ichnological aspects of incised-valley fill systems from the Viking Formation of the Western Canada Sedimentary Basin, Alberta, Canada, *in* R. W., Dalrymple, R., Boyd, and B. A., Zaitlin (Eds.), Incised Valley Systems: Origin and Sedimentary Sequences. Society of Economic Paleontologists Mineralogists Special Publication no. 51, p. 129–157.

**MacEachern, J. A., Raychaudhuri, I.** and **Pemberton, S. G. (**1992) Stratigraphic applications of the *Glossifungites* ichnofacies: delineating discontinuities in the rock record, *in* S. G., Pemberton (Ed.), Applications of Ichnology to Petroleum Exploration, a Core Workshop, Tulsa. Society of Economic Paleontologists and Mineralogists Core Workshop 17, p. 169–198.

**MacEachern, J. A., Zaitlin, B. A.** and **Pemberton, S. G. (**1999) A sharp-based sandstone of the Viking Formation, Joffre Field, Alberta, Canada: criteria for recognition of transgressively incised shoreface complexes. Journal of Sedimentary Research Section B, 69, p. 876–892.

**MacEachern, J. A., Bann, K. L., Pemberton, S. G.** and **Gingras, M. K.** (2007) The ichnofacies paradigm: high-resolution paleoenvironmental interpretation of the rock record, *in* J. A. MacEachern, K. L. Bann, M. K. Gingras and S. G. Pemberton (Eds.), Applied Ichnology. Society for Sedimentary Geology Short Course Notes, 52, p. 27–64.

**MacEachern, J.A.** and **Gingras, M.** (2007) Recognition of brackish-water trace-fossil suites in the Cretaceous Western Interior Seaway of Alberta, Canada, *in* Bromley, R., Buatois, L.A., Mangano, M.G., Genise, J. Melchor, R. (Eds.), Sediment-Organism Interactions: A Multifaceted Ichnology. Society for Sedimentary Geology Special Publication, 88, p. 149–193.

**Mángano, M. G., Buatois, L. A., West, R.** and **Maples, C.** (2002) Ichnology of a Pennsylvanian equatorial tidal flat – the Stull Shale Member at Waverly, Eastern Kansas. Kansas Geological Survey Bulletin 245, 133 p.

**McCabe, H. R.** (1959) Mississippian stratigraphy of Manitoba. Department of Mines and Natural Resources, Mines Branch, Manitoba Publication 58-1, 99 p.

**Meissner, F. F.** (1978) Petroleum Geology of the Bakken Shales Formation, Williston Basin North Dakota and Montana, in Proceedings of 1978 Williston Basin Symposium. Montana Geological Society, Billings, p. 207–227.

**Nordquist, J. W. (**1953) Mississippian stratigraphy of northern Montana, in J., Parker, ed., 4$^{th}$ annual field conference guidebook, Billings, Montana. Billings Geological Society, p. 68–82.

**Pemberton, S. G.** and **Gingras M. K.** (2005) Classification and characterizations of biogenically enhanced permeability. American Association of Petroleum Geologists Bulletin, 89, p. 1493–1517.

**Pemberton, S. G., Spila, M., Pulham, A. J., Saunders, T., MacEachern, J. A., Robbins, D.** and **Sinclair, I. K.** (2001) Ichnology and sedimentology of shallow to marginal marine systems. Geological Association of Canada Short Course, 15, 343 p.

**Pollastro, R. M., Cook, T. A., Roberts, L. N. R., Schenk, C. J., Lewan, M. D., Anna, L. O., Gaswirth, S. B., Lillis, P. G., Klett, T. R.** and **Charpentier, R. R.** (2008) Assessment of undiscovered oil resources in the Devonian-Mississippian Bakken Formation, Williston Basin Province, Montana and North Dakota, 2008. U.S. Geological Survey Fact Sheet 2008–3021, 2 p. (http://pubs.usgs.gov/fs/2008/3021/) Accessed March 12, 2011

**Reynolds, A. D.** (1999) Dimensions of paralic sandstone bodies. American Association of Petroleum Geologists Bulletin, 83, p. 211–229.

**Sandberg, C. A., Morrow, J. R.** and **Ziegler, W.** (2002) Late Devonian sea-level changes, catastrophic events and mass extinctions, *in* C. Koeberl, and K. G., MacLeod (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond. Geological Society of America Special Paper 356, p. 473–487.

**Seilacher, A.** (1967) Bathymetry of trace fossils. Marine Geology, 5, p. 413–428.

**Seilacher, A.** (1990) Aberrations in bivalve evolution related to photo- and chemosymbiosis. Historical Biology, 3, p. 289–311.

**Smith, M. G., Bustin, R. M.** and **Caplan, M. L.** (1995) Sequence stratigraphy of the Bakken and Exshaw formations: a continuum of black shale formations in the Western Canada Sedimentary Basin, *in* L. D. V., Hunter, and R. A., Schalla (Eds.), 7th International Williston Basin Symposium. Montana Geological Society Special Publication, p. 399–409.

**Smith, M. G.** and **Bustin, R. M.** (2000) Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, Western Canada Sedimentary Basin: a sequence stratigraphic interpretation. American Association of Petroleum Geologists Bulletin, 84, p. 940–960.

**Taylor, A. M.** and **Goldring, R.** (1993) Description and analysis of bioturbation and ichnofabric. Geological Society of London, Journal, 150, p. 141–148.

**Tomkin, N. S., McIlroy, D., Meyer, R.** and **Moore-Turpin, A.** (2010) Bioturbation influence of reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne'dArc Basin, offshore Newfoundland, Canada. American Association of Petroleum Geologists Bulletin, 94, p. 1059–1078.

**Uchman, A.** (2007) Deep-sea ichnology: development of major concepts, in trace fossils: concepts, problems, prospects, *in* W. Miller III (Ed). Elsevier, Amsterdam, p. 248–267.

**Webster, R. W.** (1982) Analysis of petroleum source rocks of the Bakken Formation (Devonian and Mississippian) in North Dakota. University of North Dakota, unpublished Master thesis, 150 p.

**Webster, R. W.** (1984) Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota, *in* J. Woodward, F., Meissner, and J. Clayton (Eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region, Denver, Colorado. Rocky Mountain Association of Geologists, p. 57–82.

**Yang, B., Gingras, M. K., Pemberton, S. G.** and **Dalrymple R. W.** (2008) Wave-generated tidal bundles as an indicator of wave-dominated tidal flats. Geology, 36, p. 39–42.

# 3. ICHNOLOGY OF A LATE DEVONIAN–EARLY CARBONIFEROUS LOW-ENERGY SEAWAY: THE BAKKEN FORMATION OF SUBSURFACE SASKATCHEWAN, CANADA: ASSESSING PALEOENVIRONMENTAL CONTROLS AND BIOTIC RESPONSES

## Abstract

*In spite of the high interest on the Late Devonian–Early Carboniferous Bakken Formation as one of the most important oil plays in North America and the numerous studies carried out in this unit, no ichnological analysis has been presented yet. Based on conventional sedimentological data, previous studies of the Bakken interpreted the unit as formed entirely under open-marine conditions. However, integration of ichnology has been key to the identification of not only open-marine but also brackish-water marginal-marine conditions. Based on the geometry of the sedimentary bodies and the sequence-stratigraphic framework, the brackish-water interval is interpreted as an embayment with limited or intermittent connection to the open sea. Salinity, oxygen content, and storms are regarded as the most important environmental parameters that controlled the distribution and nature of the trace fossils in the Bakken Formation. Sparse bioturbation, relatively low ichnodiversity, and the "impoverished"* Cruziana *ichnofacies characterize the marginal-marine deposits, suggesting stressful brackish-water conditions. Marine deposits from the middle member, in contrast, are highly bioturbated, with a moderate ichnodiversity and the "distal"* Cruziana *ichnofacies that flourished during fully marine well-oxygenated conditions. Although there is only a slight difference between the total ichnodiversity of the open-marine interval and that of the brackish-water interval, commonly the brackish-water facies display very low ichnodiversity. Lack of bioturbation in the black shale of the lower and upper members resulted from anoxic conditions. The passage from anoxic (lower member) to well-oxygenated conditions (middle member) was gradational, as is revealed by the occurrence of oxygen-deficient trace-fossils at the top of the lower member. Finally, the contrasting styles in tempestite preservation in upper-offshore deposits from the lower and upper open-marine intervals is attributed to variations in the intensity and frequency of storm during deposition of the highstand and transgressive deposits.*

## 3.1. INTRODUCTION

In spite of the increased attention given to the Late Devonian–Early Carboniferous Bakken Formation of southern Saskatchewan, Canada, due to its hydrocarbon potential (Christopher, 1961; LeFever et al., 1991; Smith et al., 1995; Smith and Bustin, 1995; Smith and Bustin, 1996; Smith and Bustin, 2000; Kreis et al., 2005; Kreis et al., 2006; Kohlruss and Nickel, 2009), an ichnological analysis has not yet been presented. Previous models imply fully-marine conditions during deposition of the whole Bakken Formation (Smith et al., 1995; Smith and Bustin, 2000; Kohlruss and Nickel, 2009). However, integration of ichnological and sedimentological data reveals the presence of intervals representing brackish-water marginal-marine environments, in addition to those formed under fully-marine conditions.

The aims of this chapter are to: (1) characterize the Bakken Formation ichnofauna; (2) discuss environmental parameters during deposition and the associated biotic response; and (3) integrate ichnological data with sedimentological and stratigraphic information in order to produce a more robust depositional model of this unit.

The study area is located in southeastern Saskatchewan (Township 1 to 11, Range 3 to 25 W2), covering approximately 29,900 $km^2$. For this study, sixty-two well cores were slabbed and described (Fig. 3.1).

## 3.2. GEOLOGICAL AND STRATIGRAPHIC FRAMEWORK

The Bakken Formation occurs in subsurface Saskatchewan, Manitoba, North Dakota and Montana, and records part of the infill of the Williston Basin during the Late Devonian – Early Carboniferous. In Saskatchewan, it unconformably overlies the Big Valley and Torquay formations, and it is, in turn, overlain by the Souris Valley Beds (Smith et al., 1995; Christopher, 1961; LeFever et al., 1991). Toward the west, in Alberta and British Columbia, the Bakken lower and middle members are correlated with the Exshaw Formation, whereas the upper middle member is equivalent to the basal shale of the Banff Formation (MacDonald, 1956). To the north, in west-central Saskatchewan, the unit is truncated by the sub-Mesozoic unconformity (Smith et al., 1995).

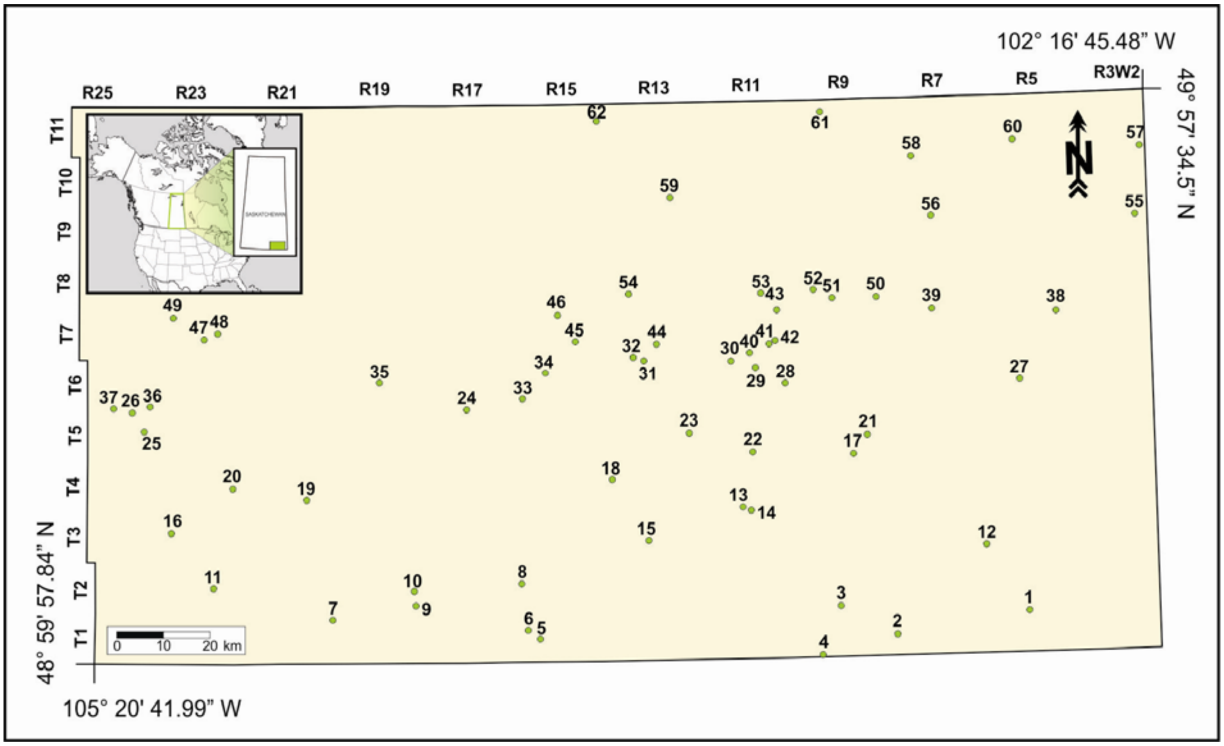



Figure 3.1 – Map of the study area showing well cores analyzed for this study (see Chapter 1 for well ID's).

The Bakken Formation is subdivided into three members: the lower and upper members both consisting of black shale, and a much more heterogeneous calcareous/dolomitic sandy-silty middle member. In southeastern Saskatchewan the range in thickness for the lower member is 0–18 m; 0–25 m for the middle member, and 0–8.6 m for the upper member (Kreis et al., 2005). The middle member has been informally subdivided into units and subunits by several authors (Christopher, 1961; Thrasher, 1985; LeFever et al., 1991; Kreis et al., 2006; Angulo and Buatois, in press). In this paper, we have subdivided the middle member into units A, B, and C; units A and B have been in turn, subdivided into subunits A1 and A2, and B1 and B2, respectively (Angulo and Buatois, in press) (Fig. 3.2).

Biostratigraphic data based on conodonts suggest that the Bakken Formation is Late Devonian–Early Carboniferous in age (Hayes, 1985; Karma, 1991). According to these authors, the lower member is Famennian, while the upper member is Kinderhookian. Identification of the Late Devonian–Early Carboniferous boundary is difficult due to the scarce recovery of conodonts between the shales from the lower and upper members, but it is assumed to be within the middle member.

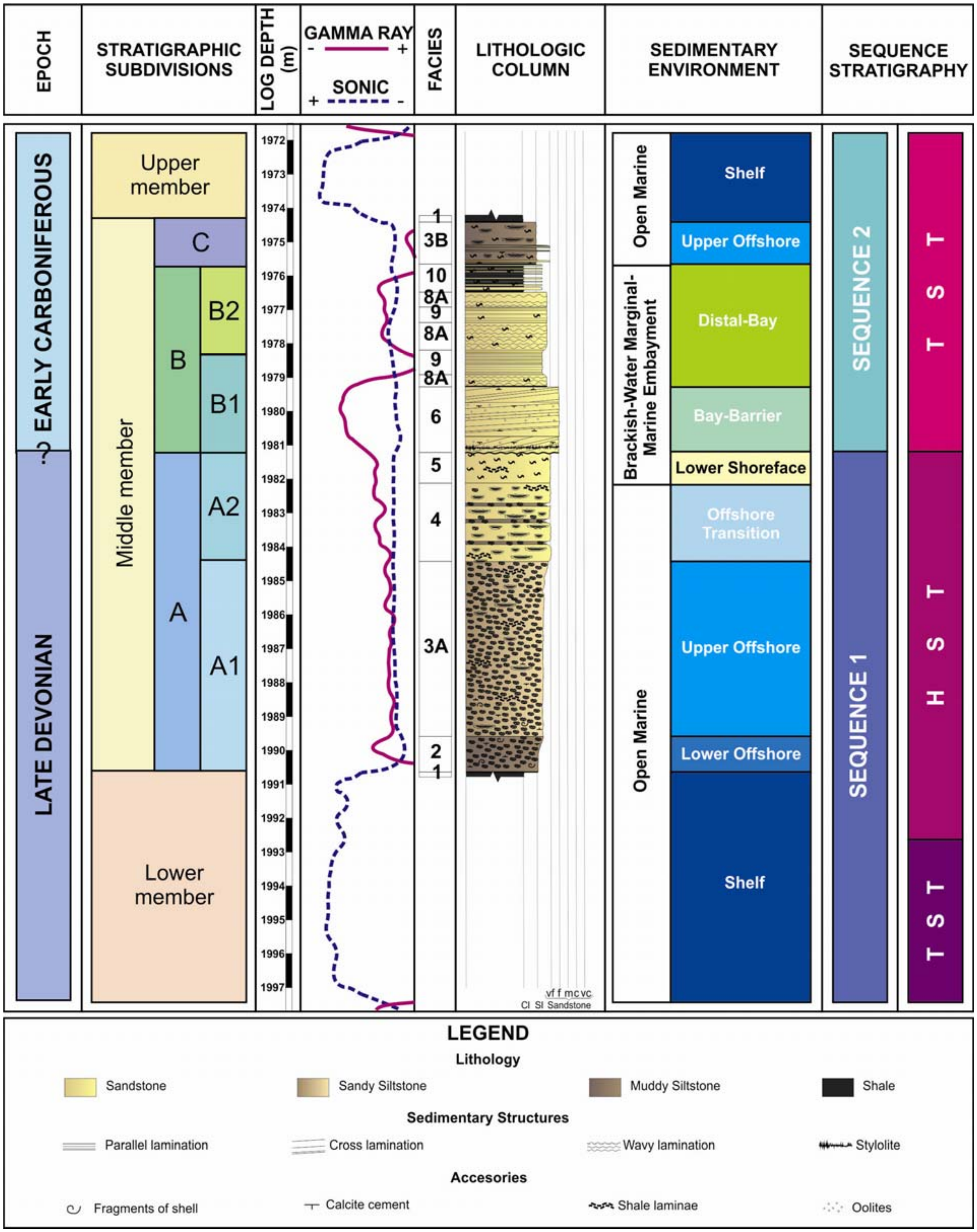



Figure 3.2 – Core log of well N° 13 (15–31–3–11W2), showing age, stratigraphic subdivisions, gamma ray and sonic wireline logs, sedimentary facies, sedimentary environments, and sequence stratigraphy of the Bakken Formation.

The Acadian unconformity, which underlies the Bakken Formation, was formed when most of the Williston Basin and eastern cratonic platform were exposed to erosion and reworking as a consequence of a sea-level drop during the Late Devonian. This sea-level drop was followed by a eustatic sea-level rise near the end of the Late Devonian (Johnson et al., 1985). During this transgression, much of the North American craton was covered by a shallow epicontinental sea, where marine black shales, including the Bakken lower shelfal unit, were deposited throughout a series of silled intracratonic basins (Smith and Bustin, 1998; Algeo et al., 2007). The upper part of the lower member, which comprises shelf deposits, and the lower part of the middle member embracing from bottom to top, lower/upper offshore, offshore-transition and distal delta-front/shoreface deposits (unit A) record the progradation of an open shoreline into this epicontinental sea during a highstand systems tract. Subsequently, a drastic sea-level drop followed by a sea-level rise occurred, and a brackish-water embayment was formed (unit B) during the early transgression. Angulo et al. (2008), and Angulo and Buatois (2011, in press) suggested that the Late Devonian–Early Carboniferous boundary occurs between unit A and B, representing a coplanar surface which was formed due to a eustatic sea-level fall that, according to Sandberg et al. (2002), resulted from the Devonian Southern Hemisphere glaciation. Neither lowstand nor forced-regressive deposits are found in the study area due to bypass, or because they were eroded by the subsequent transgression. As the transgression continued, fully-marine conditions were re-established in the entire study area, and the brackish-water deposits were locally mantled in the south-eastern region by a transgressive lag, which was in turn, regionally overlain by upper-offshore deposits (unit C). As the transgression continued, the shelfal black shale from the Bakken upper member was deposited (Fig. 3.2). See Chapter 2 for more detail about the sequence stratigraphy of the Bakken.

## 3.3. Trace-Fossil Distribution and Associated Sedimentary Facies

In this study, eleven sedimentary facies, grouped into two facies assemblages (open marine and brackish-water marginal marine), have been recognized based on lithology, physical sedimentary structures, bioturbation index, and trace-fossil content (Table 3.1). Accordingly, the Bakken Formation was subdivided into three intervals: a lower open-marine interval, a middle

Table 3.1A - Sedimentological and ichnological characteristics of the sedimentary facies defined in southeastern Saskatchewan

| Facies | Lithology | Sedimentary Structures | Bioturbation Index | Ichnofossils | Sedimentary Environments |
|---|---|---|---|---|---|
| 1 | Black shale, pyrite and rare fragments of shells locally present | Massive, locally parallel lamination and injection cracks. | 0; locally 1 at the top | *Chondrites* isp. and *Thalassinoides* isp. *Zoophycos* isp. occurs in outcrops of the Exshaw Fm. | Shelf |
| 2 | Greenish gray, burrow-mottled, muddy siltstone, commonly calcareous, with fragments of brachiopod shells and crinoids | Massive with burrow mottled texture. | 5 to 6 | *Phycosiphon incertum*, burrow mottlings | Lower Offshore |
| 3A | Light gray or greenish gray, burrow-mottled, sandy siltstone to silty very fine-grained sandstone, commonly calcareous, pyritic, locally with brachiopod shell remains and discontinuous thin laminae of shale | Massive. Discrete beds are absent or extremely rare, but sandier and siltier zones are detected through the interval. Very rarely very thin parallel lamination occur in the sandier intervals. | 5 | Dominant ichnotaxa: *Phycosiphon incertum* and *Nereites missouriensis*. Subordinate ichnotaxa: *Asterosoma* isp., *Techichnus rectus*, and *Planolites montanus*. Rare element: *Rosselia* isp. | Upper Offshore (low intensity and frquency of storms) |
| 3B | Interbedded dark gray highly bioturbated siltstone and light gray, very fine-grained sandstone | Very thin lamination occur in the sandstones. Locally, wave ripples occur on top of the parallel-laminated beds. | Highly variable: in the siltstones 6; in the sandstones 0 to 1 | Dominant elements in the siltstones: *Phycosiphon incertum* and *Nereites missouriensis*. Dominant elements in the sandstones *Techichnus rectus*. Rare element: *Siphonichnus eccaensis* | Upper Offshore (moderate intensity and frquency of storms) |
| 4 | Interbedded light gray, massive, very fine-grained sandstone and siltstone. Deposits are generally slightly to moderate calcareous | Bed boundaries are diffused. Locally continuous shale laminae occur. | 4 to 5 | Dominant elements: *Nereites missouriensis*, and *Planolites montanus*. Subordinate ichnotaxa: *Phycosiphon incertum*, and *Asterosoma* isp. Rare element: *Rosselia* isp. | Offshore Transition |
| 5 | Interbedded light gray, massive, very fine-grained sandstone with muddy partings (< 1 mm) and thinly laminated very fine-grained sandstone | Massive with common intervals of wavy or parallel lamination. Continuous shale laminae occur. | Highly variable: in the maasive intervals 4 to 5; in the laminated intervals 0 to 1 | Dominant elements: *Planolites montanus*. Subordinate elements *Nereites missouriensis*, *Phycosiphon incertum*, and *Asterosoma* isp. | Lower Shoreface |

Table 3.1B- Sedimentological and ichnological characteristics of the sedimentary facies defined in southeastern Saskatchewan

| Facies | Lithology | Sedimentary Structures | Bioturbation Index | Ichnofossils | Sedimentary Environments |
|---|---|---|---|---|---|
| 6 | Light brownish gray, fine-grained sandstone, well sorted, calcareous, locally with oolites and pyrite | Erosive-based high-angle planar cross-stratified, some intervals are massive or present parallel lamination/low-angle cross-stratification. | 0 | None | Barrier Bar |
| 7 | Light gray, very fine-grained sandstone, well sorted, with mud drapes | Flaser bedded, with wave and current ripples, climbing ripples and mudstone drapes (1 mm to 8 cm thick) are also common. | 0 | None | Wave-Dominated Tidal Flat |
| 8A | Light to dark gray, beige and locally light red, commonly pyritic, in places slightly calcareous, very fine-grained sandstone | Wavy lamination, mudstone drapes, microfaults occur rarely. | 1 to 2 | *Planolites montanus* and burrow mottlings | Barrier Bar, Margin Bay |
| 8B | Light to dark gray very fine-grained sandstone, shale laminae are common; locally mud clasts occur (< 5mm) | Burrow mottled texture, irregular shale laminations, common soft deformation structures and rare microfaults occur. | 3 to 4 | Dominant elements: *Planolites montanus*, *Phycosiphon incertum*. Rare elements: *Nereites missouriensis* and *Teichichnus rectus* | Distal Bay |
| 8C | Light gray, very fine-grained sandstone with common shale laminae | Mudstone drapes are common (< 3 mm) and occur rhytmically, locally inclined heterolithic stratification and parallel lamination are also present. | 2 to 3 | *Planolites montanus* | Tidal Flat |
| 9 | Dark gray, very thinly interlaminated, very fine-grained sandstone and muddy siltstone, locally calcareous | Parallel lamination, locally current ripples cross-lamination and mudstone drapes. | 0 to 1 | *Planolites montanus* | Margin Bay |
| 10 | Very thinly interlaminated dark gray, mudstone and light gray, silty very fine-grained sandstone | Horizontal thin parallel lamination, locally mudstone drapes, syneresis cracks are also present, sandstone lenses and wave ripples occur. | 3 to 4 | Dominant ichnotaxa: *Planolites montanus* and *Teichichnus rectus*. Rare elements: *Thalassinoides* isp., *Rosselia* isp., and *Siphonichnus eccaensis* | Distal Bay |
| 11 | Sharp-based and poorly sorted coquina with sandy matrix | Massive with burrow mottled texture | 0 to 1 | Burrow mottling | High energy ravinement during drowning of the bay |

brackish-water marginal-marine interval, and an upper open-marine interval (Fig. 3.2). This is in sharp contrast with previous interpretations, which suggested open-marine conditions for the entire unit (Smith et al., 1995; Smith and Bustin, 1996, 2000; Kohlruss and Nickel, 2009). Detailed facies description and paleoenvironmental interpretations are presented in Angulo et al. (2008), and Angulo and Buatois (2009).

Ten ichnotaxa were identified in cores of the Bakken Formation in southeastern Saskatchewan and in the type section of the Exshaw Formation in Jura Creek, Alberta: *Asterosoma* isp., *Chondrites* isp., *Nereites missouriensis*, *Phycosiphon incertum*, *Planolites montanus*, *Rosselia* isp., *Siphonichnus eccaensis*, *Teichichnus rectus*, *Thalassinoides* isp., and *Zoophycos* isp. (Fig. 3.3, Table 3.2).

Table 3.2 – Comparison in the ichnogenera found in open-marine and brackish-water marginal marine deposits.

| **Environment** | **Open-Marine** | **Brackish-Water Marginal Marine** |
|---|---|---|
| **Ichnogenera** | *Asterosoma* isp<br>*Chondrites* isp.<br>*Nereites missouriensis*<br>*Phycosiphon incertum*<br>*Planolites montanus*<br>*Rosselia* isp<br>*Siphonichnus eccaensis*<br>*Teichichnus rectus*<br>*Thalassinoides* isp.<br>*Zoophycos* isp | *Nereites missouriensis*<br>*Phycosiphon incertum*<br>*Planolites montanus*<br>*Rosselia* isp<br>*Siphonichnus eccaensis*<br>*Teichichnus rectus*<br>*Thalassinoides* isp. |

The paleoenvironmental subdivisions used in this paper are based on the terminology of MacEachern et al. (1999a) for open-marine settings, and of MacEachern and Gingras (2007) for brackish-water bay deposits. In the scheme adopted for open-marine deposits, the shoreface is located between the low tide line and the fair-weather wave base, the offshore between the fair-weather wave base and the storm wave base, and the shelf below the storm wave base. In the terminology for bay systems, these are subdivided into restricted or barrier-barred bays and open or non-barred bays. In turn, bays are subdivided into distal-bay, bay-margin and bay-mouth deposits, being the latter only limited to restricted bays. For estimation of bioturbation index (BI), Taylor and Goldring (1993) scheme was used.

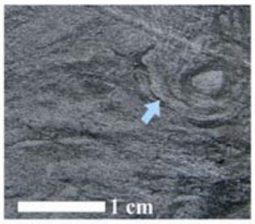
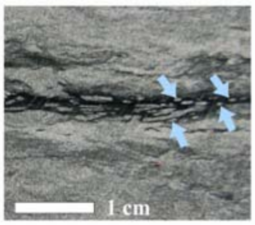
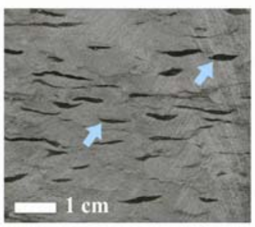
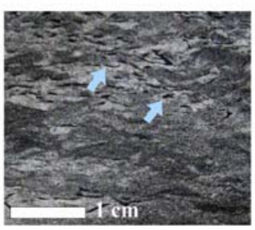
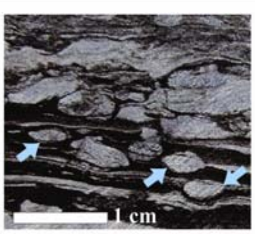
| ***ASTEROSOMA* ISP.** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|---|---|---|---|---|
|  | Star-shapped burrow system with more-or-less circular centre from which bulbous arms, tapering toward ends radiate (Otto,1854). *Asterosoma* combines burrow systems in which waste material is stowed away in the form of radial backfills, producing tensional stress to the oldest and outermost layers which get thinner or develop longitudinal cracks and microfaults (Seilacher, 2007). In core is common to recognize the arms which tend to be circular in cross section and consist of concentric lamination of sand and clay packed around a central tube (Pemberton et al., 2001). | F3A<br>F4<br>F5 | Upper Offshore<br>Offshore Transition<br>Lower Shoreface | "Distal"<br>*Cruziana* |
| ***CHONDRITES* ISP.** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|  | Regularly branching system forming a dendritic network of small cylindrical regularly ramifying tunnel systems which never anastomose, interpenetrate or cut across one another. Tunnel fill differs from host rock (Sternberg, 1833). In core, *Chondrites* commonly appears as an array of small elliptical dots which result from the truncation of the numerous branching tunnels. | F1<br>F3A | Shelf<br>Upper Offshore | "Distal"<br>*Cruziana* |
| ***NEREITES MISSOURIENSIS*** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|  | Horizontal to rarely oblique, winding, meandering to exceptionally coiled traces composed of transverse scalariform ridges along entire length of trace. Envelope zone consisting of coarser-grained lobes are commonly present on both sides of the tunnel (Weller, 1899). Tunnels are filled by less dense, fine-grained material while envelope zones are enriched in coarse grains compared to the tunnel fill/host rock (Wetzel, 2002). In core, the tunnels commonly have crescent shape and are filled with clay. In some cases the envelope zone surrounding the tunnels can be recognized. | F3A<br>F3B<br>F4<br>F5<br>F8B | Upper Offshore<br>Offshore Transition<br>Lower Shoreface<br>Distal Bay | "Distal"<br>*Cruziana* |
| ***PHYCOSIPHON INCERTUM*** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|  | Horizontal structures comprising recurving shaped lobes. Core of curved segments surrounded by a sediment mantle. The protrusive displacement of a J-shaped tube result in a spreite, but its preservation is typically poor (Wetzel and Bromley, 1994). In core, *Phycosiphon incertum* appears with a central core of clay-grade material surrounded by a bioturbated zone of clay-poor silt or very fine-grained sand (Bednarz and McIlroy, 2009) | F2<br>F3A<br>F3B<br>F4<br>F5<br>F8B | Lower Offshore<br>Upper Offshore<br>Offshore Transition<br>Lower Shoreface<br>Distal Bay | "Distal"<br>*Cruziana*<br>"Impoverished"<br>*Cruziana* |
| ***PLANOLITES MONTANUS*** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|  | Horizontal, subcylindrical, unlined, typically unbranched, straight to tortuous structure. Trace fill essentially structureless, differing in lithology from host rock (Pemberton and Frey, 1982). In core, *Planolites montanus* is circular to elliptical in shape. | F3A<br>F4<br>F5<br>F8A<br>F8B<br>F8C<br>F9<br>F10 | Upper Offshore<br>Offshore Transition<br>Lower Shoreface<br>Distal Bay<br>Margin Bay<br>Tidal Flat<br>Wave-Dominated Tidal Flat | "Distal"<br>*Cruziana*<br>"Impoverished"<br>*Cruziana* |

Figure 3.3A – Summary of the composition of the Bakken ichnofauna, including a brief description of each ichnotaxon in 3D and in core view, representative photographs, and the associated sedimentary facies, paleoenvironments, and ichnofacies.

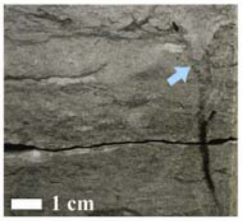
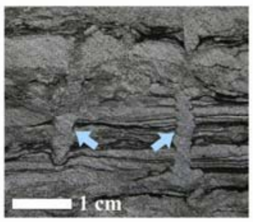
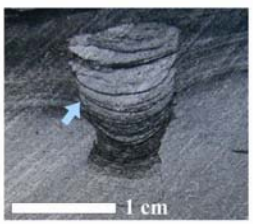
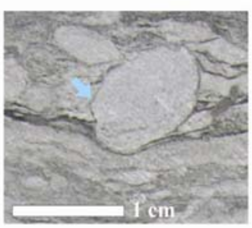
| ***ROSSELIA* ISP.** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|---|---|---|---|---|
|   | Bulb-like to funnel-like burrow, vertical to oblique, generally tapering downward, with inner cylindrical tube. The bulb is filled with concentric layers of finer grained sediment (Nara, 1995). In core, *Rosselia* commonly appear with funnel shape and a concentric infill. | F3A<br>F4<br>F10 | Upper Offshore<br>Offshore Transition<br>Distal Bay | "Distal" *Cruziana*<br>"Impoverished" *Cruziana* |
| ***SIPHONICHNUS ECCAENSIS*** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|   | Vertical structures containing a backfill of concave-downward menisci. The laminae that form the backfill are cut through centrally by a vertical tube, filled with pale, massive sand. In bedding plane view, burrow diameter is 20-28 mm and central tube diameter is approximately 9-11 mm (Stanistreet et al., 1980). In cores *Siphonichnus eccaensis* appears as a vertical burrow. | F10<br>F3B | Upper Offshore<br>Distal Bay | "Distal" *Cruziana*<br>"Impoverished" *Cruziana* |
| ***TEICHICHNUS RECTUS*** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|   | Simple to flat U-shaped burrow, horizontal to slightly inclined, unbranched, locally thickly lined having retrusive spreiten composed of vertically to subvertically stacked laminae (Seilacher, 1955). In split-core sections, *Teichichnus* appears commonly as a vertical series of tightly packed concave-up crescentric laminae. | F3A<br>F3B<br>F8B<br>F10 | Upper Offshore<br>Distal Bay | "Distal" *Cruziana*<br>"Impoverished" *Cruziana* |
| ***THALASSINOIDES* ISP.** | **DESCRIPTION** | **SEDIMENTARY FACIES** | **SEDIMENTARY ENVIRONMENT** | **ICHNOFACIES** |
|   | Cylindrical, smooth-walled burrows forming 3-dimensional branching systems consisting of horizontal network connected to surface by more or less vertical shafts (Ehrenberg, 1944). In core, *Thalassinoides* isp. appears sub-circular to elliptical in cross-section, very thinly lined to essentially unlined. | F10 | Shelf<br>Distal Bay | "Impoverished" *Cruziana* |

Figure 3.3B – Summary of the composition of the Bakken ichnofauna, including a brief description of each ichnotaxon in 3D and in core view, representative photographs, and the associated sedimentary facies, paleoenvironments, and ichnofacies.

### 3.3.1. Lower Open-Marine Interval

The lower open-marine interval comprises the Bakken lower member and unit A of the middle member (Fig. 3.2). It consists of a shallow-marine progradational parasequence, which records at the bottom shelf black shale (facies 1), overlain by lower-offshore calcareous and fossiliferous muddy siltstone (facies 2), which grades upward into upper-offshore dolomitic sandy siltstone to silty very fine-grained sandstone (subfacies 3A), followed by offshore-transition interbedded massive very fine-grained sandstone and siltstone (facies 4). Locally, in the southern and southwestern region of the study area, lower-shoreface interbedded massive very fine-grained sandstone and thinly laminated very fine-grained sandstone occur (facies 5). With the exception of the contact between the black shale (facies 1) of the lower member and the muddy siltstone (facies 2) of the middle member, which is sharp but conformable, all the contacts in the lower open-marine interval are gradational, and the changes from one facies to the other are so subtle that it is often difficult to locate facies boundaries (Angulo and Buatois, 2009, 2010).

With the exception of a few wells in which *Chondrites* isp. and *Thalassinoides* isp. occur at the contact between shelf and lower-offshore deposits (lower and middle member), shelf deposits from the lower member are unbioturbated. In contrast, lower-offshore deposits are intensely bioturbated (BI 5–6), and characterized by burrow mottlings. Only *Phycosiphon incertum* is recognized in these deposits. Lack of lithologic contrast makes the recognition of discrete biogenic structures difficult. Upper-offshore deposits are also thoroughly bioturbated (BI 5). The trace-fossil assemblage is dominated by *Phycosiphon incertum* and *Nereites missouriensis*. *Planolites montanus*, *Asterosoma* isp., and *Teichichnus rectus* are also common, while *Rosselia* isp and *Chondrites* isp are very rare. Offshore-transition deposits are intensely burrowed (BI 4–5), having *Nereites missouriensis* as the dominant element, *Phycosiphon incertum* and *Asterosoma* isp. as subordinate ichnotaxa, and *Rosselia* isp. as a rare component. Finally, lower-shoreface deposits have a variable degree of bioturbation with some intervals ranging from 0 to 1 and others from 4 to 5. The trace-fossil assemblage includes abundant *Planolites montanus*, while *Nereites missouriensis*, *Phycosiphon incertum* and *Asterosoma* isp. are common.

Deposits of the lower open-marine interval are characterized by the “distal” *Cruziana* ichnofacies (*sensu* MacEachern et al., 1999a), being dominated by feeding traces of deposits feeders. Although the bioturbation degree in lower-offshore, upper-offshore and offshore-transition deposits is high, ichnodiversity is moderate. The moderate ichnodiversity of the open-marine facies can be explained in part as a taphonomic effect in which deeper-tier fauna, such as the producers of *Phycosiphon incertum* and *Nereites missouriensis*, under low rates of sedimentation, reworked the sediments, destroying shallower-tier structures, and producing a mottled background. As a result, only the deeper-tier biogenic structures can be recognized. In shallow-marine deposits containing abundant trace fossils, *Phycosiphon incertum* is generally a late-stage component of the ichnofabric, cross-cutting and reworking earlier burrow fills (Goldring et al., 1991; McIlroy, 2007). However, taphonomy alone cannot explain the observed pattern; the reduced diversity may be a consequence of the Late Devonian mass extinction. The evolutionary implications of the Bakken ichnofauna will be addressed elsewhere.

### 3.3.2. Middle Brackish-Water Marginal-Marine Interval

The middle brackish-water marginal-marine interval overlies the lower open-marine deposits, and comprises unit B of the Bakken middle member (Fig. 3.2). Angulo et al. (2008) interpreted this interval as been deposited in an estuary formed during an early transgression which followed a sea-level drop at the top of the lower open-marine interval. However, the dimensions of this supposed incised valley greatly exceed those typically reported in the geological record for this type of systems (Reynolds, 1999; Gibling, 2006). In addition, the typical tripartite zonation present in most incised valleys (Dalrymple et al., 1992) cannot be recognized in these brackish-water deposits. Finally, whereas most incised valleys are oriented perpendicular to the shoreline, the Bakken marginal-marine deposits would have implied an incised valley oriented parallel to the coastline. Another possible interpretation for this interval is that of a delta. However, the progradational stacking pattern characteristic of deltas, in which deltaic parasequences are stacked forming progradational parasequence sets is not recognized in the Bakken middle member. In addition, no deltaic channels or delta-plain deposits have been identified. Therefore, based on the geometry and orientation of the sedimentary bodies and the sequence-stratigraphic framework, the brackish-water marginal-marine interval was subsequently interpreted by Angulo and Buatois (2011, in press) as an embayment with limited or intermittent connection to the open sea.

At the bottom of the brackish-water marginal-marine interval, in the central region of the study area, high and low-angle planar cross-stratified, massive fine-grained sandstone (facies 6) occurs. This facies is interpreted as a barrier bay, oriented northwest-southeast, which migrated towards the northeast as the transgression progressed (Angulo and Buatois, 2011, in press). In the south-western region of the study area, previously formed barrier bars may have been eroded due to ravinement during the transgression; in this region, only distal-bay deposits were preserved. Where the barrier bay is present, the contact between the brackish-water marginal-marine deposits and the underlying open-marine deposits is sharp and erosive, and is interpreted as an amalgamated sequence boundary/transgressive surface. On the other hand, where the barrier-bar deposits are absent, the boundary looks gradational. Barrier-bay deposits are followed by distal-bay, margin-bay and tidal-flat deposits, which consist of wavy-bedded very fine-grained sandstone (subfacies 8A), very fine-grained sandstone with common irregular shale laminations (subfacies 8B), very fine-grained sandstone with common mud drapes and locally inclined heterolithic stratification (subfacies 8C), very thinly interlaminated very fine-grained sandstone and muddy siltstone (facies 9), and very thinly interlaminated mudstone and very fine-grained silty sandstone (facies 10). Distal-bay and margin-bay facies cover most of the study area, interfinger and reoccur vertically. In the west/southwestern portion of the study area, a wave-dominated tidal flat is present, being characterized by flaser-bedded very fine-grained sandstone (facies 7).

Barrier-bay deposits are essentially unbioturbated, whereas distal-bay, margin-bay and tidal-flat deposits show a more variable bioturbation degree. Facies 9, for example, is unbioturbated, whereas those of subfacies 8A and 8C are poorly bioturbated (BI 1–2), and contain monospecific suites of *Planolites montanus*. Facies 10 is mostly moderately bioturbated (BI 3–4), containing *Planolites montanus* and *Teichichnus rectus*, with *Rosselia* isp. and *Siphonichnus eccaensis* locally present. Subfacies 8B is also moderately bioturbated (BI 3–4), being *Planolites montanus* and *Phycosiphon incertum* dominant, and *Nereites missouriensis* and *Teichichnus rectus*, rare.

Deposits of the brackish-water marginal-marine interval are characterized by the "impoverished" *Cruziana* ichnofacies (*sensu* MacEachern et al., 1999a) with low to moderate bioturbation degree, a relatively low ichnodiversity, and dominance of feeding traces of deposit feeders.

### 3.3.3. Upper Open-Marine Interval

The upper open-marine interval embraces unit C of the middle member and the upper member of the Bakken Formation (Fig. 3.2). At the bottom of this interval, in the southeastern region of the study area, a thin transgressive lag (facies 11) was preserved. Upper-offshore interbedded siltstone and parallel laminated very fine-grained sandstone (subfacies 3B), reflecting the alternation of fair-weather conditions and storm events, covered the entire study area, overlying the previous lag and the brackish-water marginal-marine deposits. The basal contact of the upper open-marine deposits is erosive where the transgressive lag is present, and gradational where it overlies the fine-grained bay deposits. As the relative-sea level rose, the entire area was capped by shelf black shale (facies 1) from the upper member. The contact between upper-offshore and shelf deposits is sharp but conformable.

The transgressive lag at the bottom of the interval is characterized by burrow mottlings and a low bioturbation degree (BI 0–1). No discrete ichnotaxa were identified. The bioturbation degree in the upper-offshore deposits is very variable. The siltstone is intensively bioturbated (BI 6), whereas the sandstone is poorly bioturbated (BI 0–1). However, lack of lithologic contrast makes identification of trace fossils in the siltstone difficult. The trace-fossil assemblage includes *Nereites missouriensis* and *Phycosiphon incertum*, these being dominant in the siltstone beds, and rare *Teichichnus rectus* in sandstone beds. Locally, *Siphonichnus eccaensis* is present. Shelf deposits of the upper member are unbioturbated.

The upper interval containing open-marine deposits is characterized by the “distal” *Cruziana* ichnofacies. As well as the open-marine deposits of the lower interval, in spite of a relatively high bioturbation degree, ichnodiversity is moderate, and the ichnofauna is dominated by feeding traces of deposits feeders.

### 3.4. Environmental Controls and Biotic Response

#### 3.4.1. Salinity: Open-Marine vs. Restricted Ichnofaunas

It has been widely documented that salinity is an important limiting factor in trace-fossil distribution (MacEachern and Pemberton, 1994; Mángano and Buatois, 2004; MacEachern and Gingras, 2007; Buatois and Mángano, 2011). Physical sedimentary structures are mainly salinity-independent, but biogenic structures are not, and therefore, trace-fossil information is very useful for paleosalinity reconstructions (Buatois et al., 1997).

Water bodies are classified based upon salinity in freshwater (less than 0.5‰); brackish water (0.5–30‰); seawater (30–40‰); and hypersaline water (more than 40‰). Brackish-water assemblages are colonized by opportunistic euryhaline-tolerant species (MacEachern and Gingras, 2007) that have developed the ability to control osmotic flooding and ionic concentrations of body fluids, in order to survive reduced salt concentrations (Croghan, 1983) and that have also developed different behavioral adaptations as a different strategy to cope with salinity fluctuations. In contrast, open-marine and freshwater environments are typically colonized by stenohaline organisms that can tolerate only very minor changes in salinity (Bromley, 1996).

According to Mángano and Buatois (2004), trace-fossil assemblages developed under normal-marine salinity in nearshore to offshore environments are characterized by: (1) high ichnodiversity; (2) marine ichnotaxa produced by both euryhaline and stenohaline organisms; (3) onshore-offshore trends displayed by the *Skolithos* and *Cruziana* ichnofacies; (4) occurrence of both infaunal and epifaunal trace fossils; (5) presence of simple and complex structures produced by presumed trophic generalists and specialists, respectively; (6) presence of multispecific associations, which become more common towards distal settings; (7) high density; and (8) wide size ranges.

Marginal-marine settings, such as estuaries, deltas, bays and lagoons, typically display steep salinity gradients which depend mostly on the interaction between the amount of freshwater input, either from rivers, rainfall, runoff, and the open-ocean coastal waters. Salinity fluctuations, combined with variations in other parameters such as temperature, oxygen content, turbidity, substrate consistency and sedimentation rates, result in a physiologically stressful environment for numerous organisms (Pemberton et al., 2001).

As noted by Pemberton and Wightman (1992) and Pemberton et al. (2001), brackish-water assemblages are characterized by: (1) low diversity; (2) forms typically found in marine environments; (3) simple structures constructed by tropic generalists; (4) suites that are commonly dominated by a single ichnogenus; (5) vertical and horizontal ichnofossils that are common to both the *Skolithos* and *Cruziana* ichnofacies; (6) abundance of some ichnotaxa; (7) presence of monospecific suites; and (8) diminished size compared to fully marine counterparts.

While previous interpretations suggest open-marine conditions for the entire Bakken Formation (Smith et al., 1995; Smith and Bustin, 2000; Kohlruss and Nickel, 2009), integration of ichnological and sedimentological data reveals the presence of a brackish-water marginal-marine interval. According to Buatois et al. (2005), and MacEachern and Gingras (2007), discrimination of brackish-water successions requires comparison with open-marine deposits of the same basin. The Bakken Formation comprises an excellent example, in which open-marine and brackish-water marginal marine deposits can be compared in the same stratigraphic unit, revealing that the Bakken ichnofauna was strongly controlled by salinity (Fig. 3.4). With the exception of the black shale of the lower and upper members, intervals formed under open-marine conditions (units A and C) are characterized by a high bioturbation index, moderate ichnodiversity, and the "distal" *Cruziana* ichnofacies (Fig. 3.5). In contrast, brackish-water marginal-marine deposits (unit B) are typified by a low bioturbation index, relatively low ichnodiversity, and the "impoverished" *Cruziana* ichnofacies (Fig. 3.6).

Notably, when the total number of ichnogenera found in the open-marine and the brackish-water intervals are compared (Table 3.2), only a slight difference is found. Whereas ten ichnogenera are recognized in the open-marine interval, seven ichnogenera are distinguished in the brackish-water marginal-marine interval. This indicates that ichnodiversity should not be considered at face value and in isolation when evaluating stress levels during deposition. Rather, the taxonomic composition of the ichnofauna, burrow size, the population strategies involved (r-vs K-selected), the styles of colonization, and the associated degree and uniformity of bioturbation need to be evaluated as well (MacEachern and Bann, 2008). Certain ichnofabrics are particularly diagnostic of stressed, brackish-water settings. For example, sparsely bioturbated beds containing monospecific or paucispecific suites of *Planolites montanus* or *Teichichnus rectus* are dominant in the marginal-marine deposits of the Bakken. This ichnofabric is common in modern and ancient brackish-water deposits elsewhere (Buatois et al., 2005; Buatois and Mángano, 2011). Additionally, the occurrence of physical sedimentary structures in unit B reflecting tidal influence, such as mud drapes and flaser bedding, and the presence of syneresis cracks which have been related to salinity changes (Plummer and Gostin, 1981), support the brackish-water embayed nature of this interval.

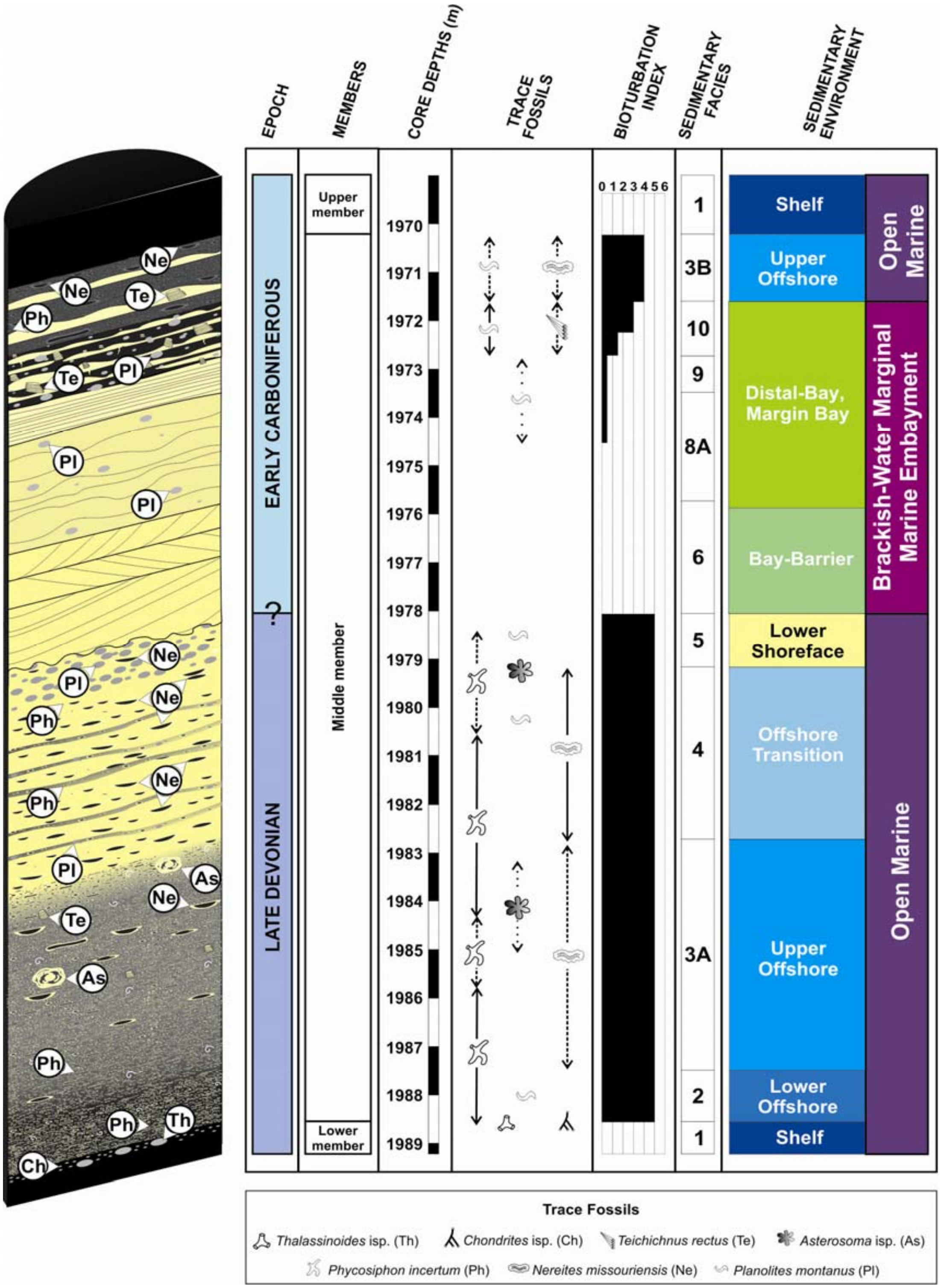



Figure 3.4 – Core log of well 15–31–03–11W2 showing the vertical succession of the depositional environments of the Bakken Formation, sedimentary facies, age, trace fossils, and bioturbation index. Note the high bioturbation degree that characterizes the open-marine facies (with the exception of facies 1, whose lack of bioturbation is attributed to anoxic conditions), in contrast with the sparse bioturbation recognized in the brackish-water marginal-marine facies.

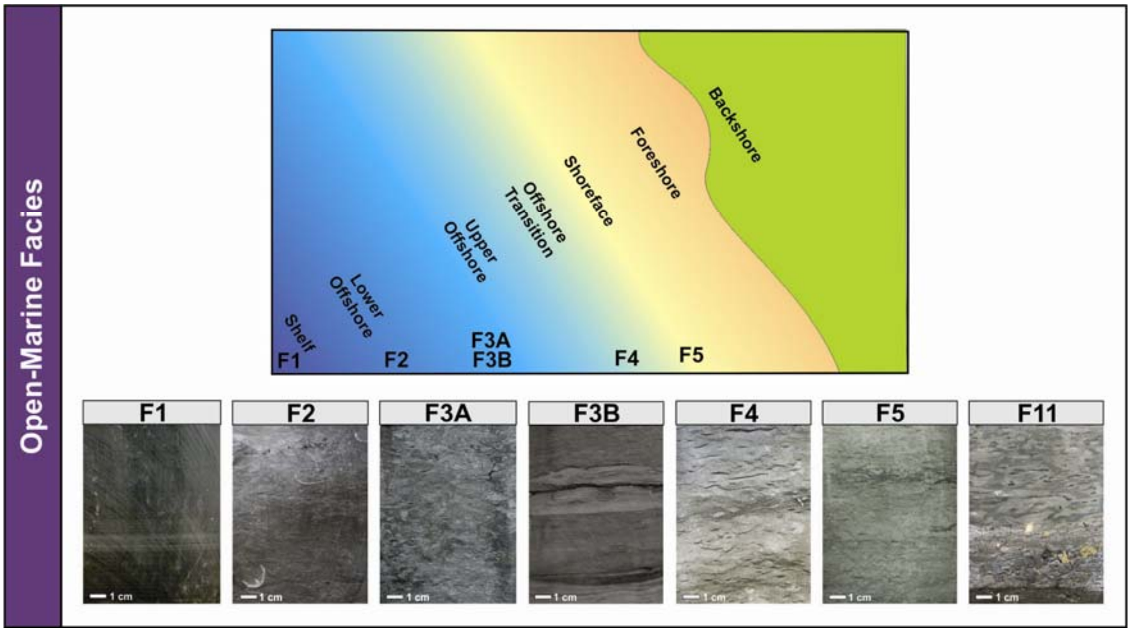



Figure 3.5 – Schematic depositional model for the open-marine intervals showing the interpreted subenvironments for the sedimentary facies of the Bakken Formation in southeastern Saskatchewan. Core photographs for each open-marine sedimentary facies are shown. Facies 11 corresponds to a transgressive lag. (F1) 10–1–2–19W2, 2274.7 m. (F2) 6–11–4–21W2, 2157.83 m. (F3A) 14–15–2–23W2, 2156.8 m. (F3B) 8–11–8–14W2, 1595.5 m. (F4) 3–9–6–16W2, 1888.57 m. (F5) 3–18–3–13W2, 2065.7 m. (F11) 5–31–6–13W2, 1818.6 m.

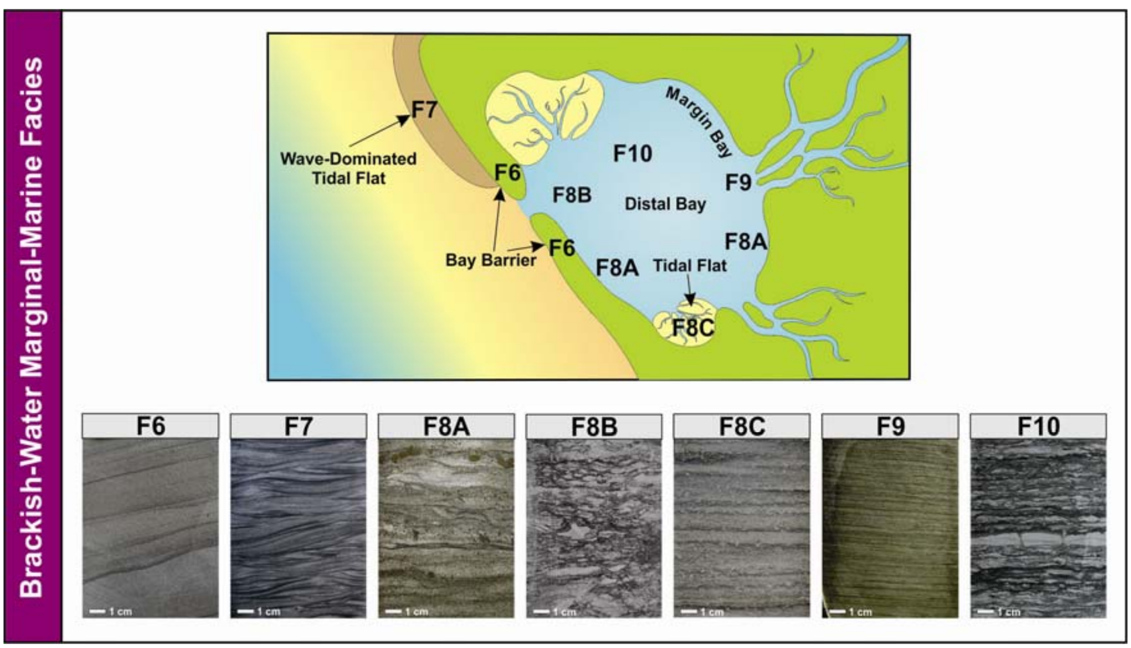



Figure 3.6 – Schematic depositional model of the brackish-water marginal-marine embayment showing the interpreted subenvironments for the sedimentary facies of the Bakken Formation in southeastern Saskatchewan. Core photographs for each brackish-water marginal-marine sedimentary facies are shown. (F6) 10–15–1–16W2, 2335.25 m. (F7) 6–13–2–19W2, 2727.2 m. (F8A) 5–31–6–13W2, 1704.87 m. (F8B) 6–11–4–21W2, 2144.91 m. (F8C) 14–15–2–23W2, 2151.5 m. (F9) 3–4–7–11W2, 1725.8 m. (F10) 9–36–5–25W2, 1818.6 m.

Lack of or sparse bioturbation in bay-mouth deposits (facies 6, 7) might record heightened deposition rates and hydrodynamic energy, in addition to a salinity stress. Distal-bay, margin-bay and tidal-flat deposits (facies 9, 10, subfacies 8A, 8B and 8C), in contrast, display a more variable range in degree of bioturbation (BI 0–4), probably due to highly variable salinities. Lack of bioturbation in facies 9 and sparse bioturbation in subfacies 8A and 8C may indicate strongly brackish-water conditions, while more intense bioturbation in facies 10 and subfacies 8B (BI 3–4) may suggest a stronger open-marine signal at times when the embayment had a major connection with open-sea waters. The presence of ichnogenera reflecting the behaviors of organisms that are highly sensitive to physiological stress, such as *Phycosiphon incertum* and *Nereites missouriensis* (MacEachern and Gingras, 2007; Buatois et al., 2008) in subfacies 8B, and the transitional nature of the contact between facies 10 and open-marine deposits (subfacies 3B) is consistent with this environmental scenario.

### 3.4.2. The Role of Oxygen Content

Oxygenation is one of the most important factors controlling the character and behavior of benthic organisms, particularly in quiet marine basinal environments (Savrda, 2007). Hence, ichnofabrics are useful to reconstruct the paleoceanographic conditions that prevailed during deposition of pelagic and hemipelagic muds, since they can serve as proxy indicators of paleo-oxygenation.

The ichnofabrics of well-oxygenated pelagic/hemipelagic substrates typically display well-developed tiering patterns. Berger et al. (1979) and Ekdale et al. (1984) noted two main vertical zones in the sediment: the surface mixed layer and the transition layer. The surface mixed layer represents a relatively fluid zone of rapid and complete biogenic homogenization, in which no discrete traces are recognized. Underlying this zone lies the transition layer, which is characterized by the heterogeneous mixing produced by the activity of organisms that live or feed at greater depths in the substrate (Savrda 1992, 2007). As deposition occurs, the mixed and transition layers migrate upwards and sediments pass into the historical layer below reach of active bioturbation. Ichnofabrics, therefore, include a homogeneous or vaguely burrow-mottled background formed in the surface mixed layer, and a superimposed suite of well-defined discrete traces emplaced in the transition layer. Through time, ichnocoenosis originated under well-oxygenated conditions will be characterized by a high diversity of transition-layer structures (Savrda, 2007).

Earlier studies of modern marine environments have recognized the impact that changes in bottom-water oxygenation has in the character of infaunal communities and their associated bioturbation (Rhoads and Morse, 1971; Pearson and Rosenberg, 1978; Savrda et al., 1984). As bottom-water oxygen concentrations decrease, the thickness of the mixed layer generally decreases as well as diversity, diameter, and penetration depths of transition-layer structures. Eventually, if oxygen concentrations drop below a critical threshold level (~ 0.1 ml/l dissolved oxygen), bioturbation virtually ceases altogether, and laminated, organic-rich sediments accumulate (Savrda, 1992, 2007).

Ichnological data reflect well-oxygenated conditions during deposition of the Bakken middle member (Fig. 3.5). The ichnofabrics of the upper-offshore and offshore-transition deposits are characterized by a burrow-mottled background in which *Planolites montanus* is the only ichnotaxon identified. Transition-layer structures include abundant *Nereites missouriensis* and *Phycosiphon incertum*, and more rarely *Asterosoma* isp., *Teichichnus rectus*, *Rosselia* isp., and *Chondrites* isp. Silty to sandy sedimentary facies, typified by light colors and low organic matter content, also suggest normal-oxygenated conditions. Additionally, studies of modern *Nereites missouriensis* in the South China Sea by Wetzel (2002) indicate that the *Nereites* producers appear to be restricted to oxygenated sedimentary environments. According to this author, *Nereites* occurs above the redox boundary marked by a dark-colored zone stained by manganese oxides that rests on top of greenish to gray sediments. The distance between the manganese-stained horizon and the horizontal part of the burrows is fairly constant in the range of about 1 to 2 cm. *Nereites* never penetrates into the manganese-stained muds or into the underlying gray greenish muds. The close spatial relationship of the horizontal parts of the *Nereites* burrows to the redox boundary suggests that the animal fed on microbes that are known to occur there in high concentrations (Wetzel, 2002).

The common lack of bioturbation, the black color, and high organic matter content (an average of 8% TOC with a maximum value of 20% for the lower member and an average of 10% TOC and a maximum value of 35% for the upper member, according to Smith and Bustin, 1996), and thin lamination suggest slow sedimentation rates and mostly anoxic conditions during deposition of most of the lower and upper members on a shelf, below storm wave base. MacEachern et al. (1999b) cautioned about the assumption that all seemingly unbioturbated black shales are anoxic, noting that the apparent absence of bioturbation may be a taphonomic artifact. According to this line of thought, biogenic structures may have been emplaced close to the sediment-water interface in a soupy substrate, but during burial, dewatering and compaction, these structures become impossible to detect due to lack of lithologic contrast and reordering of clay particles.

In the case of the Bakken black shale, independent paleontologic data also support an anoxic to strongly dysaerobic setting. In North Dakota, Thrasher (1985) identified brachiopods, gastropods, cephalopods, bivalves, ostracods and arthropod remains, as well as fish scales in the lower member, and almost no megafossils, with the exception of a few planktonic forms, in the upper member. Hayes (1985) mentioned that the scarce benthic fauna and the presence of conodonts and fish remains suggest that an oxygenated zone existed above anoxic bottom conditions for the lower and upper shales in North Dakota. Furthermore, Thrasher (1985) noted that the fauna in the lower shale consists entirely of epibenthic forms, with no evidence of infaunal forms. In the same vein, the lack of infauna in coeval similar deposits of eastern United States (Blocher Formation) has been related to reducing conditions below the sediment-water interface (Ettensohn and Barron, 1981).

Although the black shales of the lower and upper members of the Bakken Formation are commonly laminated and unbioturbated, *Chondrites* isp. and *Thalassinoides* isp. occur at the top of the lower member in a few cores in southeastern Saskatchewan. Additionally, *Zoophycos* isp. was found in outcrops at the same stratigraphic level at the top of the basal black shale of the Exshaw Formation in Crowsnest Lake (roadcut on Highway 3), Alberta. The *Chondrites*-*Zoophycos* ichnoguild represents an “oxygen-deficient” situation. The tolerance and/or preference of *Chondrites* and *Zoophycos* to oxygen-deficient substrates can be explained due to a strategy, in which the organisms benefit from an oxygen-deficient substrate rich in food, while maintaining contact with more oxygenated bottom waters via an open burrow (Savrda, 1992). The occurrence of *Chondrites* isp. and *Zoophycos* isp. at the top of the black shale of the lower member reflects an increase in oxygen concentration but still deficient of interstitial waters between the anoxic conditions that prevailed during deposition of the black shale of the lower member and the more oxygenated conditions existing at the time the middle member was deposited (Fig. 3.7).

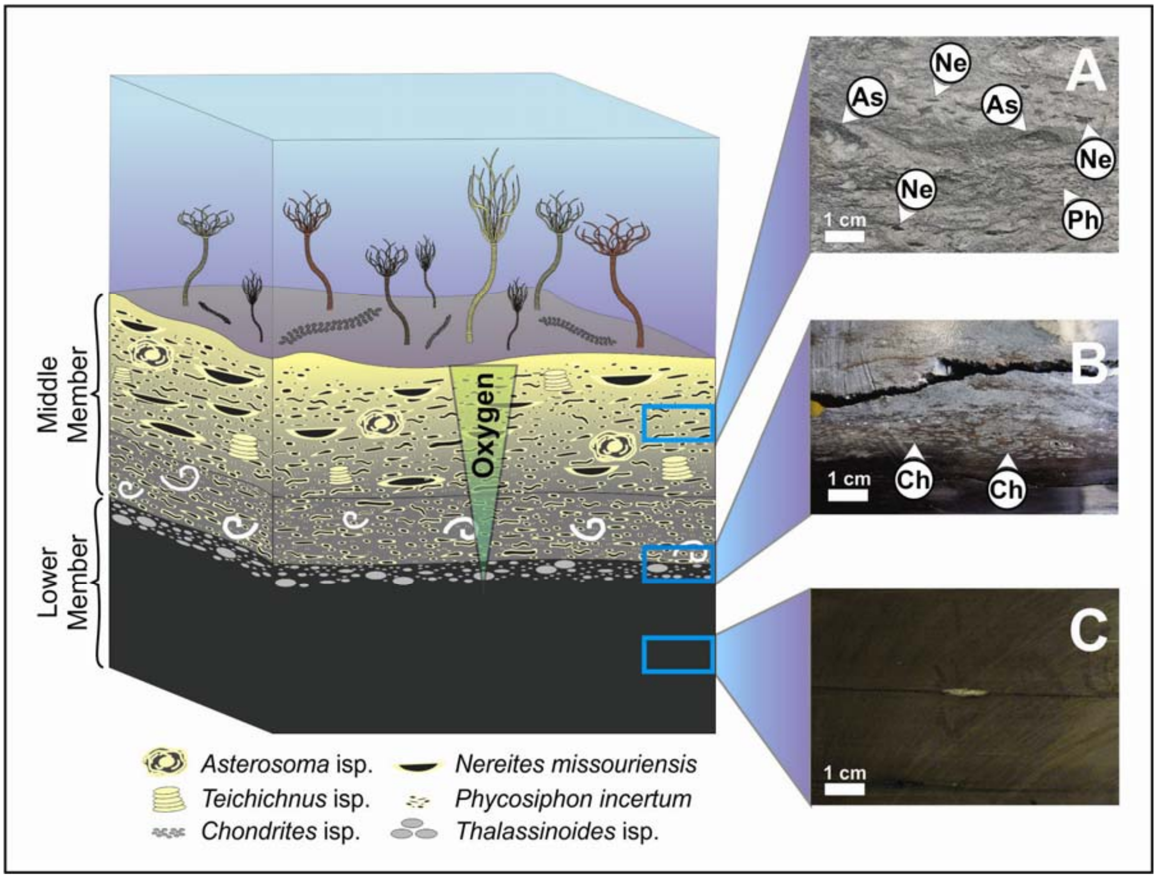



Figure 3.7 – Schematic diagram showing the transition between the mostly anoxic deposits of the lower member and the well-oxygenated deposits of the middle member. At the top of the black shale of the lower member, oxygen-deficient trace fossils (*Chondrites* isp. and *Thalassinoides* isp.) occur right below the well-oxygenated sediments of the middle member. Core photographs showing compressed *Chondrites* isp. and small *Thalassinoides* isp. at the contact between the lower and the middle member. (A) 7–32–3–11W2, 1996.82 m. (B) 1–11–7–11W2, 1608.76 m. (C) 3–25–6–16W2, 1777 m.

Ekdale and Mason (1988) presented an oxygen-controlled trace-fossil model that relates the dominance of different ethologic groups when oxygen concentration of the interstitial water in sediments is increased. According to their model, a transition from fodinichnia-dominated through pascichnia-dominated to domichnia-dominated trace-fossil associations occurs, as oxygen concentration of interstitial water in sediment increases. Although the presence of *Thalassinoides*, which is commonly regarded as a domichnia made by a variety of suspension-feeder crustaceans, together with oxygen deficient ichnofauna at the top of the black shale of the lower member could seem contradictory to the Ekdale and Mason model, there is a plausible explanation. This ichnogenus has been also interpreted by some authors either as the work of deposit feeders (Ekdale, 1985) or farmers that culture bacteria at depth within their burrows (Savrda, 1992). Therefore, some authors considered *Thalassinoides* as a fodinichnion or an agrichnion (e.g. Bromley, 1990; Ekdale and Bromley, 1991).

Ekdale and Mason (1988) noted that dysaerobic and some anaerobic deposits are commonly characterized by a very high-density and very low-diversity association of trace fossils created by deposit-feeding organisms. While feeding on unoxidized organic material in the subsurface, deposit-feeding animals may circulate oxygenated bottom-water down from the sea floor through semipermanent shafts to allow them to respire. The local occurrence of *Thalassinoides* isp. and *Chondrites* isp. at the top of the lower member in southeastern Saskatchewan, and *Zoophycos* isp. in outcrops of the Exshaw Formation in Alberta can be explained due to the maintenance of a connection to the sea floor and bottom waters, like many producers of fodinichnia. Moreover, the presence of *in situ* or locally reworked benthic macrofauna remains (Thrasher, 1985) near the upper contact of the lower member is also consistent with periods of more hospitable conditions on the sea floor during initial and final stages of the lower black-shale deposition.

Smith and Bustin (2000) also mentioned the presence of *Chondrites* at the top of the lower member, and regarded this ichnogenus as indicative of the *Glossifungites* ichnofacies. According to these authors, the presence of the *Glossifungites* ichnofacies was an evidence of a sea-level fall, and interpreted the contact between the lower and the middle member as a sequence boundary. However, *Chondrites* is a feeding structure produced either by deposit feeders or by chemosymbionts that actively filled their burrows (Seilacher, 1990; Fu, 1991; Bromley, 1996). Accordingly, it cannot be interpreted as an evidence of the *Glossifungites* ichnofacies since the latter is characterized by sharp-walled, unlined, passively filled, dwelling burrows of suspension feeders or passive predators (Seilacher, 1967; MacEachern et al., 1992; Buatois and Mángano, 2011). In addition, specimens of *Chondrites* and *Thalassinoides* at the top of the lower member are compressed, indicating subsequent substrate compaction and emplacement in a softground rather than a firmground (Angulo and Buatois, in press) (Fig. 3.8).

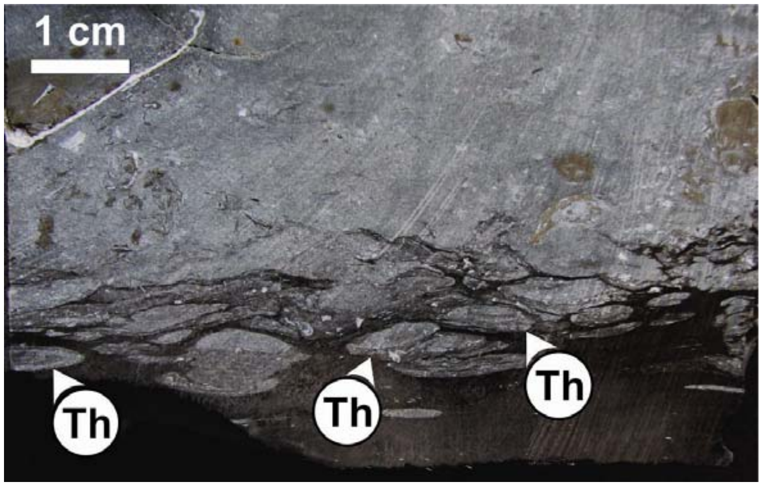



Figure 3.8 –- Core photograph (6–11–4–21W2, 2158.56 m) illustrating the bioturbated contact between the black shale of the lower member (facies 1) and the calcareous and fossiliferous muddy siltstone of the middle member (facies 2). Note intense compression of *Thalassinoides* isp. due to compaction.

### 3.4.3. The Impact of Storm Intensity and Frequency in Tempestite Preservation

Tempestite preservation depends on net sedimentation rate, the biogenic mixing rate, and the magnitude of physical reworking (Pemberton and MacEachern, 1997; Pemberton et al., 2001). Wheatcroft (1990) proposed a model for tempestite preservation focusing on time scales, which involves the time necessary to bury the event bed beyond the reach of the burrowing infauna (transit time) and the time required to biogenically destroy the event bed (dissipation time). This author calculated the transit time by adding the thickness of the biogenic reworking zone and one half the thickness of the event layer, all divided by the sedimentation rate. Dissipation time, moreover, is comparatively more difficult to determine, and depends on more factors, namely the nature of the bed (mineralogy, chemistry, lithology, fabric), the characteristics of the benthic community, which can produce little or much greater disruption of the bed depending on their size, and particularly the organism behavior. The latter depends, in turn, on the dynamic interplay between the benthic community and the depositional event itself, the desirability of the event bed as a site for colonization and as a repository of food resources, and the absolute time available for burrowing. Pemberton et al. (2001) pointed out that the preservation potential also depends on storm intensity and frequency. The low preservation potential of hurricane-induced tempestites may also reflect the infrequent nature of such disturbances, in which the storm layer is exposed to long periods of biogenic colonization and modification before burial below the reach of infauna. In high latitudes, where storm activity varies cyclically, with storms more frequent and of higher-magnitude in the winter than during the summer time, tempestites accumulate rapidly during winter seasons with little or no time for biogenic reworking, while summer fair-weather seasons favour biogenic colonization and modification of the tempestites.

Upper-offshore deposits in the Bakken show two different textures depending on tempestite preservation. Upper-offshore deposits from the lower open-marine interval lack discrete tempestites due to intense biogenic reworking during fair-weather conditions (Fig. 3.9A). Storm events are only recorded by poorly defined bands that are comparatively richer in sandy sediment in comparison with the surrounding fine-grained fair-weather deposits. In contrast, upper-offshore deposits from the upper open-marine interval commonly display discrete storm beds characterized by parallel-laminated very fine-grained sandstone interbedded with intensely bioturbated siltstone, indicating that fair-weather conditions were interrupted by storm events (Fig. 3.9B).

Comparison between upper-offshore deposits from lower (subfacies 3A) and upper (subfacies 3B) open-marine intervals does not reflect any significant difference between the lithology, trace-fossil association, and magnitude of the physical reworking. The difference in tempestite preservation in the upper-offshore deposits from these two intervals could be in principle attributed to a difference in sedimentation rate or storm intensity and frequency. However, a difference in sedimentation rate is hard to reconcile with the sequence-stratigraphic context. In this case, a lower sedimentation rate for the basal progradational upper-offshore deposits and a higher sedimentation rate for the upper retrogradational upper-offshore deposits should be invoked in order to explain the total obliteration of the storm events in the former (due to a long transit time) and their preservation in the latter (as a result of a short transit time). However, higher sedimentation rates would be expected in the highstand systems tract and not in the transgressive systems tract. Therefore, a different frequency and intensity of storm events in the basal and upper marine intervals is the most likely factor to explain the difference in tempestite preservation. In this scenario, the total reworking of storm events in the progradational basal upper-offshore deposits may have resulted from less intense and frequent storms during the highstand, while tempestites were preserved in the transgressive upper-offshore deposits of the upper interval as a consequence of more frequent and intense storms.

Supporting this idea, increased frequency of storms has been recorded in connection with postglacial sea-level rise in Holocene deposits (Blum and Price, 1998; Anderson et al., 2004).

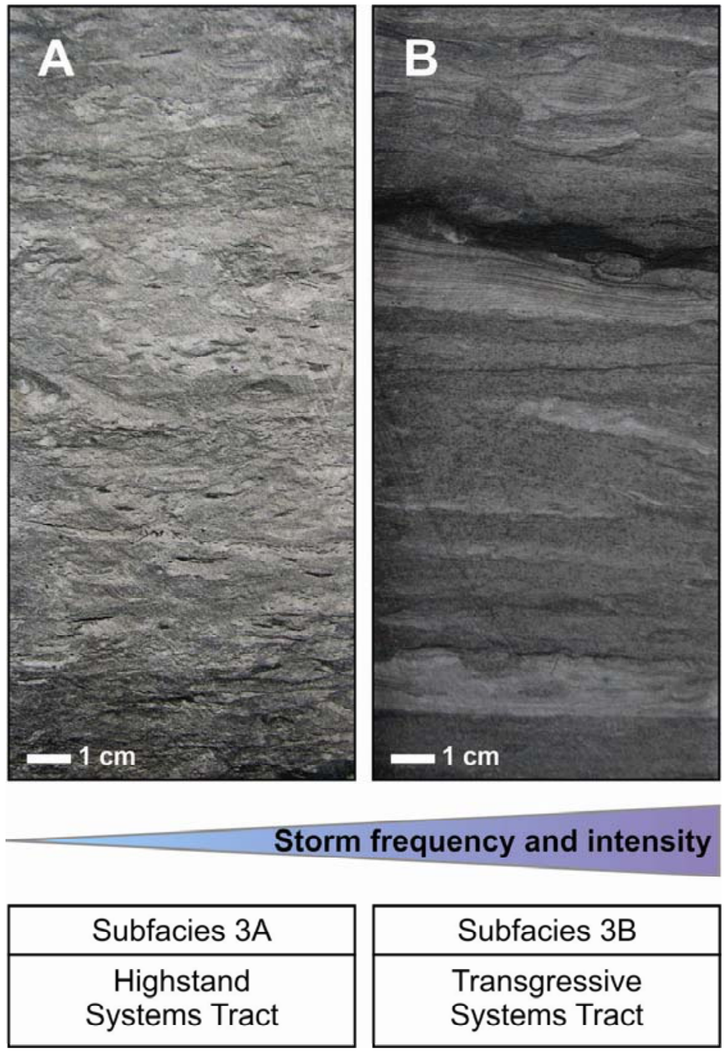



Figure 3.9 – Different styles of tempestite preservation in upper-offshore deposits (subfacies 3A, 3B) from the lower and the upper open-marine interval related to variations in storm frequency and intensity during the highstand and transgressive systems transgressive systems tract. (A) Lack of discrete tempestites due to low storm frequency and intensity in subfacies 3A. Sand-rich bands are the only evidence of storm deposition (7–32–3–11W2, 1996.82 m). (B) Common discrete storm beds reflecting higher storm frequency and intensity in subfacies 3B (7–12–7–11W2, 1693.85 m).

### 3.5. Conclusions

While previous studies in the Bakken Formation considered that the whole unit records deposition in fully marine environments, ichnological data provide evidence that a portion of this unit accumulated in a marginal-marine setting under brackish-water conditions. The lower open-marine interval (lower member and unit A of the middle member) embraces shelf, lower/upper offshore, offshore-transition deposits, and locally lower-shoreface deposits. The brackish-water marginal marine interval (unit B of the middle member) is interpreted as an embayment with restricted connection to the open sea. The upper open-marine interval (unit C of the middle member and the upper member) includes a transgressive lag, upper-offshore, and shelf deposits.

Salinity, oxygen content, and storm action are regarded as important factors controlling the style of bioturbation and trace-fossil distribution. While open-marine deposits are generally characterized by high bioturbation degree, moderate ichnodiversity, and the “distal” *Cruziana* ichnofacies, brackish-water marginal-marine deposits are distinguished by a low bioturbation degree, lower ichnodiversity, and the “impoverished” *Cruziana* ichnofacies. The slight difference between the total ichnodiversity of the open-marine interval (ten ichnogenera) and that of the brackish-water interval (seven ichnogenera) provides a cautionary note on the use of ichnodiversity in itself as a proxy for estimating stress levels. Rather, the taxonomic composition of the ichnofauna, burrow size, the population strategies involved (r- vs K-selected), the styles of colonization, and the associated degree and uniformity of bioturbation need to be evaluated in conjunction with ichnodiversity levels.

The lack of bioturbation, black color, high organic matter content, thin lamination, and scarce benthic fauna indicate anoxic conditions in shelf deposits, whereas the rest of the open-marine sediments accumulated under well-oxygenated conditions. The change from anoxic to well-oxygenated conditions represented by the contact between the lower and the upper member was gradational, as it is reflected by the appearance of an oxygen-deficient assemblage, including *Chondrites* isp., *Zoophycos* isp., and *Thalassinoides* isp. at the top of the black shale of the upper member. The presence of these ichnotaxa within the anoxic sediments of the black shale of the lower member can be explained due to the maintenance of a burrow connection to an oxygenated sea floor.

Offshore deposits from the lower and the upper open-marine intervals display two contrasting patterns of tempestite preservation. Whereas storm layers have been almost totally obliterated by biogenic reworking in the upper-offshore deposits (subfacies 3A) from the lower interval, tempestites have been preserved in the upper-offshore deposits (subfacies 3B) from the upper open-marine interval. This difference is attributed to less intense and frequent storms during the highstand, providing the organisms with sufficient time to totally rework the storm layers. In contrast, tempestites were preserved in the transgressive upper-offshore deposits of the upper interval as a consequence of more frequent and intense storms.

### 3.6. Acknowledgments

Financial support of this project has been provided by Saskatchewan Energy and Resources and University of Saskatchewan. Additional funds were granted by AAPG (Grant 2008, 2009) and IAS (Grant 2009). We want to give special thanks to the Geological Subsurface Laboratory staff in Regina, particularly to Melinda Yurkowski, Chris Gilboy, Erik Nickel, Dan Kohlruss, Chao Yang, Tyler Music, and all the technical team that displayed the cores for this study; without their support this project would have not been possible. We are also very grateful to James MacEachern and M. Gabriela Mángano, Kim Kreis, John Lake, Andrew Nimegeers, Carol Brown, Fran Haidl, and Brian Pratt for feedback. We also want to thank the Londoño family for providing free accommodation and all their support during core work in Regina, and the two anonymous Palaeo-3 reviewers for their comments.

### 3.7. References

**Algeo, T., Lyons, T., Blakey, R.** and **Over, D.** (2007) Hydrographic conditions of the Devono-Mississippian North American Seaway inferred from sedimentary Mo-TOC relationships. Palaeogeography, Palaeoclimatology, Palaeoecology, 256, p. 204–230.

**Anderson, J. B., Rodriguez, A., Abdulah, K. C., Dillon, R. H., Banfield, L. A., McKeon, H. A.** and **Wellner, J. S.** (2004) Late Quaternary stratigraphic evolution of the northern Gulf of Mexicomargin: a synthesis, *in:* Anderson, J. B., Fillon R. H. (Eds.), Late Quaternary Stratigraphic Evolution of the Northern Gulf of Mexico Margin. Society for Sedimentary Geology, Special Publication, 79, p. 1–23.

**Angulo, S.** and **Buatois, L. A.** (2009) Sedimentological and ichnological aspects of a sandy low-energy coast: Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2009, v. 1, Saskatchewan

Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-5, 17 p.

**Angulo, S.** and **Buatois, L. A.** (2010) Sedimentary facies distribution of the Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan: implications for understanding reservoir geometry, paleogeography, and depositional history. Summary of Investigations 2010, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2010-4.1, Paper A-4, 18 p.

**Angulo, S.** and **Buatois, L. A.** (2011) Petrophysical characterization of sedimentary facies from the Upper Devonian-Lower Mississippian Bakken Formation in the Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2011, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2011-4.1, 16 p.

**Angulo, S.** and **Buatois, L. A.** (in press.) Integrating depositional models, ichnology and sequence stratigraphy in reservoir characterization: the middle member of the Late Devonian–Early Carboniferous Bakken Formation of subsurface southeastern Saskatchewan revisited. American Association of Petroleum Geologists Bulletin.

**Angulo, S., Buatois, L. A.** and **Halabura S.** (2008) Paleoenvironmental and sequence-stratigraphic reinterpretation of the Upper Devonian–Lower Mississippian Bakken Formation of subsurface Saskatchewan: integrating sedimentological and ichnological data. Summary of Investigations 2008, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2008-4.1, CD-ROM, Paper A-3, 24 p.

**Bednarz, M.** and **McIlroy, D.** (2009) Three-dimensional reconstruction of "phycosiphoniform" burrows: implications for identification of trace fossils in core. Palaeontologia electronica, Vol. 12, Issue 3; 13A: 15 p. http://palaeo-electronica.org

**Berger W. H., Ekdale A. A.** and **Bryant, P. F.** (1979) Selective preservation of burrows in deep-sea carbonates. Marine Geology, 32, p. 205–230.

**Blum, M. D.** and **Price, D. M.** (1998) Quaternary alluvial plain construction in response to interacting glacio-eustatic and climatic controls, Texas Gulf Coastal Plain, *in:* Shanley, K.

W., McCabe, P. J. (Eds.), Relative Role of Eustasy, Climate and Tectonism in Continental Rocks. Society for Sedimentary Geology, Special Publication 59, p. 31–48.

**Bromley, R. G.** (1990) Trace Fossils-Biology and Taphonomy, Special Topics in Paleontology. Unwin-Hyman, London, 280 p.

**Bromley, R. G.** (1996) Trace Fossils. Biology, Taphonomy and Applications, second ed. Chapman and Hall, London, 361 p.

**Buatois, L. A.** and **Mángano, M. G.** (2011) Ichnology: Organism-substrate interactions in space and time. Cambridge University, 358 p.

**Buatois, L. A., Mángano, M. G, Maples, C. G.** and **Lanier W. P.** (1997) The paradox of nonmarine ichnofaunas in tidal rhythmites: integrating sedimentologic and ichnologic data from the Late Carboniferous of eastern Kansas, USA. Palaios, 12, p. 467-481.

**Buatois, L. A., Gingras, M. K., MacEachern, J., Mángano, M. G., Zonneveld, J. P, Pemberton, S. G., Netto, R. G.** and **Martin, A.J.** (2005) Colonization of brackish-water systems through time: Evidence from the trace-fossil record. Palaios, 20, p. 321–347.

**Buatois, L. A., Santiago, N., Parra, K.** and **Steel, R.** (2008) Animal-substrate interactions in an Early Miocene wave-dominated tropical delta: delineating environmental stresses and depositional dynamics (Tácata field, eastern Venezuela). Journal of Sedimentary Research, 78, p. 458–479.

**Christopher, J. E.** (1961) Transitional Devonian-Mississippian formations of southern Saskatchewan. Saskatchewan Department of Mineral Resources, Report 66, 103 p.

**Croghan, P. C.** (1983) Osmotic regulation and the evolution of brackish- and fresh-water faunas. Geological Society, London, 140, p. 39–46.

**Dalrymple, R. W., Zaitlin, B. A.** and **Boyd, R.,** (1992) Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology, 62, p. 1130-1146.

**Ekdale, A. A.** (1985) Paleoecology of the marine endobenthos. Palaegeography, Palaeoclimatology, Palaeoecology, 50, p. 63–81

**Ekdale, A. A.** and **Bromley, R. G.** (1991) Analysis of composite ichnofabrics: an example in uppermost Cretaceous chalk of Denmark. Palaegeography, Palaeoclimatology, Palaeoecology, 6, p. 232–249

**Ekdale, A. A.** and **Mason, T. R.** (1988) Characteristic trace-fossil associations in oxygen-poor sedimentary environments. Geology, 16, p. 720–723.

**Ekdale, A. A., Muller, L. N.** and **Novak, M. T.** (1984) Quantitative ichnology of modern pelagic deposits in the abyssal Pacific. Palaegeography, Palaeoclimatology, Palaeoecology, 45, p. 189–223.

**Ehrenberg, K.** (1944) Ergänzende Bemerkungen zu den seinerzeit aus dem Miozän von Burgschleinitz beschriebenen Gangkernen und Bauten dekapoder Krebse. Paläontologische Zeitschrift, 23, p. 354–359.

**Ettensohn, F. R.** and **Barron, L. S.** (1981) Depositional model for the Devonian-Mississippian black-shale sequence of North America: a tectono-climatic approach. Technical Information Center, Morgantown, U.S. Dept. of Energy, DOE/METC/12040-2

**Fu, S.** (1991) Funktion, Verhalten und Einteilung fucoider und lophocteniider Lebensspuren: Courier Forschunginstitut Senckenberg, 135, p. 1–79.

**Gibling, M. R.** (2006) Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. Journal of Sedimentary Research, 76, p. 731–770.

**Goldring, R., Pollard, J. E.** and **Taylor, A. M.** (1991) *Anconichnus horizontalis*; a pervasive ichnofabric-forming trace fossil in post-Paleozoic offshore siliciclastic facies. Palaios, 6, p. 250–263.

**Hayes, M. D.** (1985) Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota. Mountain Geologist, Rocky Mountain Association of Geologists, Denver, Colorado, 22, p. 64–77.

**Johnson J. G., Klapper, G.** and **Sandberg, C. A.** (1985) Devonian eustatic fluctuations in Euroamerica. Bulletin of the Geological Society of America, 96, p. 567–587.

**Karma, R.** (1991) Geology and Geochemistry of the Bakken Formation (Devonian-Mississippian) in Saskatchewan. Master's thesis, University of Regina.

**Kohlruss, D.** and **Nickel, E.** (2009) Facies analysis of the Upper Devonian-Lower Mississippian Bakken Formation, southeastern Saskatchewan. Summary of Investigations 2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-6, 11 p.

**Kreis, L. K. Costa, A.** and **Osadetz, K. G.** (2005) New perspectives on the hydrocarbon potential of Bakken and Torquay Formations, southeastern Saskatchewan, <http://www.cspg.org/conventions/abstracts/2005Core/kreis_l_ hydrocarbon_potential_bakken_torquay.pdf> Accessed March 15th 2011.

**Kreis, L. K., Costa, A.** and **Osadetz, K. G.** (2006) Hydrocarbon potential of Bakken and Torquay formations, southeastern Saskatchewan, *in:* Gilboy, C. F., Whittaker, S. G. (Eds.), Saskatchewan and Northern Plains Oil & Gas Symposium 2006. Saskatchewan Geological Society Special Publication, 19, p. 118–137.

**LeFever, J. A., Martiniuk, C. D., Dancsok, E. F. R.** and **Mahnic, P. A.** (1991) Petroleum potential of the middle Member, Bakken Formation, Williston Basin, *in:* Christopher, J. E., Haidl, F. (Eds.), Sixth International Williston Basin Symposium. Saskatchewan Geological Society Special Publication, 11, p. 74–94.

**MacDonald, G. H.** (1956) Subsurface stratigraphy of the Mississippian rocks of Saskatchewan. Geological Survey of Canada, Memoir 282, 46 p.

**MacEachern, J. A.** and **Bann, K. L.** (2008) The role of ichnology in refining shallow marine facies models; Recent advances in models of siliciclastic shallow-marine stratigraphy, *in:* Hampson, G. J., Steel, R. J., Burgess, P. B., Dalrymple, R. W. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy. Society for Sedimentary Geology Special Publication, 90, p. 73–116.

**MacEachern, J. A.** and **Gingras, M.** (2007) Recognition of brackish-water trace-fossil suites in the Cretaceous Western Interior Seaway of Alberta, Canada, *in:* Bromley, R., Buatois, L. A., Mangano, M. G., Genise, J. Melchor, R. (Eds.), Sediment-Organism Interactions: A

Multifaceted Ichnology. Society for Sedimentary Geology Special Publication, 88, p. 149–193.

**MacEachern, J. A.** and **Pemberton, S. G.** (1994) Ichnologic aspects of incised-valley fill systems from the Viking Formation of the Western Canada Sedimentary Basin, Alberta, Canada, *in:* Dalrymple, R. W., Boyd, R., Zaitlin, B. A. (Eds.), Incised Valley Systems: Origin and Sedimentary Sequences. Society of Economic Paleontologists Mineralogists Special Publication, 51, p. 129–157.

**MacEachern, J. A., Raychaudhuri, I.** and **Pemberton, S. G.** (1992) Stratigraphic applications of the Glossifungites ichnofacies: delineating discontinuities in the rock record, *in:* Pemberton, S. G. (Ed.), Applications of Ichnology to Petroleum Exploration, a Core Workshop, Tulsa. Society of Economic Paleontologists and Mineralogists Core Workshop 17, p. 169–198.

**MacEachern, J. A., Zaitlin, B. A.** and Pemberton, **S. G.** (1999a) A sharp-based sandstone of the Viking Formation, Joffre Field, Alberta, Canada: criteria for recognition of transgressively incised shoreface complexes. Journal of Sedimentary Research, 69, p. 876–892.

**MacEachern, J. A., Stelck, C. R.** and **Pemberton, S. G.** (1999b) Marine and marginal marine mudstone deposition: Paleoenvironmental interpretations based on the integration of ichnology, palynology and foraminiferal paleoecology, *in:* Bergman, K. M., Snedden, J. W. (Eds.), Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentological Interpretation. Society for Sedimentary Geology Special Publication, 64, p. 205–225.

**Mángano, M. G.** and **Buatois, L. A.** (2004) Ichnology of Carboniferous tide-influenced environments and tidal flat variability in the North American Midcontinent, *in:* McIlroy, D. (Ed.), The Application of Ichnology to Paleoenvironmental and Stratigraphic Analysis. Geological Society, London, Special Publication 228, p. 157–178.

**Mángano, M. G. Buatois, L. A., West, R.** and **Maples, C.** (2002) Ichnology of a Pennsylvanian equatorial tidal flat – the Stull Shale Member at Waverly, Eastern Kansas. Kansas Geological Survey Bulletin, 245, 133 p.

**McIlroy, D.** (2004) Some Ichnological concepts, methodologies, applications and frontiers, *in:* McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geological Society Special Publication, 228, p. 3–27.

**McIlroy, D.** (2007) Lateral variability in shallow marine ichnofabrics; implications for the ichnofabric analysis method. Journal of the Geological Society of London, 164, p. 359–369.

**Nara, M.** (1995) *Rosselia socialis* - A dwelling structure of a probable terebellid polychaete. Lethaia, 28, p. 171–178.

**Otto, E. von** (1854) Additamente zur Flora des Quadergebirges in Sachsen, part 2: Leipzing, G. Mayer, 53 p.

**Pearson, T. H.** and **Rosenberg, R.** (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanography and Marine Biology Annual Review, 16, p. 229–311.

**Pemberton, S. G.** and **MacEachern, J. A.** (1997) The ichnological signature of storm deposits: The use of trace fossils in event stratigraphy, *in:* Brett, C. E., Baird, G. C. (Eds.), Paleontological Events, Stratigraphic, Ecological and Evolutionary Implications. New York, Columbia University Press, p. 73–109.

**Pemberton, S. G.** and **Wightman, D.M.** (1992) Ichnological characteristics of brackish water deposits, *in:* Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration: A Core Workshop, Society for Sedimentary Geology Core Workshop, 17, p. 141–167.

**Pemberton, S. G.** and **Frey, R.W.** (1982) Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma. Journal of Paleontology, 56, p. 843–881.

**Pemberton, S. G., Spila, M., Pulham, A. J., Saunders, T., MacEachern, J. A., Robbins, D.** and **Sinclair, I. K.** (2001) Ichnology and sedimentology of shallow to marginal marine systems, Geological Association of Canada, Short Course Notes, 15.

**Plummer P. S.** and **Gostin, V. A.** (1981) Shrinkage cracks: desiccation or synaeresis. Journal of Sedimentary Petrology, **51**, p. 1147–1156.

**Reynolds, A.D.** (1999) Dimensions of paralic sandstone bodies. American Association of Petroleum Geologists Bulletin, 83, p. 211–229.

**Rhoads, D. C.** and **Morse, J. W.** (1971) Evolutionary and ecologic significance of oxygen-deficient basins. Lethaia, 4, p. 413–428.

**Sandberg, C. A., Morrow, J. R.** and **Ziegler, W.** (2002) Late Devonian sea-level changes, catastrophic events and mass extinctions, *in* Koeberl, C., MacLeod, K. G. (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond. Geological Society of America, Special Paper 356, p. 473–487.

**Savrda, C. E.** (1992) Trace fossil and benthic oxygenation, *in:* Maples, C. G., West, R. R. (Eds), Trace Fossils. Paleontological Society, Short Course 5, p. 172–196.

**Savrda, C. E.** (2007) Trace fossils and marine benthic oxygenation, *in:* Miller, W., III. (Ed.), Trace Fossils. Concepts, Problems, Prospects. Elsevier, Amsterdam, p. 149–156.

**Savrda, C. E., Bottjer, D. J.** and **Gorsline, D. S.** (1984) Development of a comprehensive oxygen-deficient marine biofacies model: evidence from Santa Monica, Santa Barbara and San Pedro basins, California continental borderland. American Association of Petroleum Geologists Bulletin, 68, p. 1179–1192.

**Seilacher, A.** (1955) Spuren and Fazies im Unterkambrium, *in:* Schindewolf, O.H., Seilacher, A. (Eds.), Beiträge zur Kenntnis des Kambrius in der Salt Range, Pakistan, Akademie der Wissenschaften und der Literatur zu Mainz, mathematisch- naturwissenschaftliche Klasse, Abhandlungen, 10, p. 373–399.

**Seilacher, A.** (1967) Bathymetry of trace fossils. Marine Geology, 5, p. 413–428.

**Seilacher, A.** (1990) Aberrations in bivalve evolution related to photo- and chemosymbiosis. Historical Biology, 3, p. 289–311.

**Smith, M. G.** and **Bustin, R. M.** (1995) Sedimentology of the Late Devonian and Early Mississippian Bakken Formation, Williston Basin, *in:* Hunter, L. D. V., Schalla, R. A. (Eds.), 7th International Williston Basin Symposium. Montana Geological Society, Special Publication, p. 103–114.

**Smith, M. G.** and **Bustin, R. M.** (1996) Lithofacies and paleoenvironments of the Upper Devonian and Lower Mississippian Bakken Formation, Williston Basin. Bulletin of Canadian Petroleum Geology, 44, No 3, p. 495–507.

**Smith, M. G.** and **Bustin, R. M.** (1998) Production and preservation of organic matter during deposition of the Bakken Formation (Late Devonian and Early Mississippian), Williston Basin. Palaeogeography, Palaeoclimatology, Palaeoecology, 142, p. 185–200.

**Smith, M. G.** and **Bustin, R. M.** (2000) Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, Western Canada Sedimentary Basin: a sequence stratigraphic interpretation. American Association of Petroleum Geologists Bulletin, 84, p. 940–960.

**Smith, M. G., Bustin, R. M.** and **Caplan, M. L.** (1995) Sequence stratigraphy of the Bakken and Exshaw formations: a continuum of black shale formations in the Western Canada Sedimentary Basin, *in:* Hunter, L. D. V., Schalla, R. A. (Eds.), 7th International Williston Basin Symposium. Montana Geological Society, Special Publication, p. 399–409.

**Stanistreet, I. G., Le Blanc Smith, G.** and **Cadle, A. B.** (1980) Trace fossils as sedimentological and palaeoenvironmental indices in the Ecca Group (Lower Permian) of the Taansvaal. Transactions of the Geological Society of the South Africa, 83, 333–344.

**Sternberg, K. M. G.** (1833) Versuch einer geognostich-botanischen Dartsellung der Flora der Vorwelt. Fleischer, Leipzig, Prague, v. 5–6, p. 1–80.

**Taylor, A. M.** and **Goldring, R.** (1993) Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society, London, 150, p. 141–148.

**Thrasher, L.** (1985) Macrofossils and biostratigraphy of the Bakken Formation (Devonian and Mississippian) in western North Dakota. Unpublished Master of Science Thesis, University of North Dakota.

**Weller, S.** (1899) Kinderhook faunal studies. I. The fauna of vermicular sandstone at Northview, Webster County, Missouri. Transactions of the Academy of Science St. Louis, 9, p. 9–51.

**Wetzel, A.** (2002) Modern *Nereites* in the south China Sea-ecological association with redox conditions in the sediment. Palaios, 17, p. 507–515.

**Wetzel, A.** and **Bromley, R. G.** (1994) *Phycosiphon incertum* revisited-*Anconichnus horizontalis* is its junior subjectives synonym. Journal of Paleontology, 68, p. 1,396 –1,402.

**Wheatcroft, R. A.** (1990) Preservation potential of sedimentary event layers. Geology, 18, p. 843–845.

# 4. DELINEATION OF BRACKISH-WATER EMBAYMENTS IN THE STRATIGRAPHIC RECORD: THE UPPER DEVONIAN–LOWER CARBONIFEROUS BAKKEN FORMATION, SOUTHEASTERN SASKATCHEWAN, CANADA


## *Abstract*

*Marginal-marine embayments are a common element of modern coastlines. However, relatively few examples of ancient embayments have been documented in the literature, probably because their diagnostic criteria still remain poorly understood. In addition, while much emphasis has been placed on the distinction between deltas and estuaries, alternative facies models for marginal-marine systems have been comparatively less explored. Deposits of Unit B of the Upper Devonian–Lower Carboniferous Bakken Formation are interpreted here as a brackish-water marginal-marine embayment with limited or intermittent connection to the open sea, representing a unique opportunity to improve our understanding of this depositional setting. Marginal-marine embayments, as well as deltas and estuaries, form in the coastline under the interaction of marine and terrestrial processes, which may produce similar sedimentary facies and trace-fossil assemblages. Additionally, marginal-marine embayments originate in transgressive, aggradational, and progradational settings. Therefore, different criteria are required for their discrimination of brackish-water marginal-marine embayments in the stratigraphic record. In contrast, orientation, geometry, and distribution of the sedimentary facies are key for their recognition. Detailed sedimentological and ichnological analysis of sixty-two well cores of the Bakken Formation in southeastern Saskatchewan revealed a complex mosaic of sedimentary facies which resulted from the migration of a barrier bar and embayment deposits during a punctuated transgression. The recognition of elongated mouth deposits parallel to the palaeoshoreline, the presence of brackish-water deposits beneath the seaward side of the barrier, the wide distribution of brackish-water facies that were originally deposited in localized areas, and the interfingering of facies reflecting strong marine signals with facies revealing strong brackish-water conditions are all considered as diagnostic features for the recognition of embayment deposits in the stratigraphic record. Consequently, the discrimination of these deposits is greatly compromised by the amount and distribution of the data available.*

## 4.1. INTRODUCTION

Recognition of marginal-marine brackish-water deposits in the stratigraphic record is of paramount importance from the perspective of hydrocarbon exploration and reservoir characterization. Deltaic models, particularly those based on the Mississippi Delta, became extremely popular in the oil industry during the 1960s (Shepard et al., 1960; Scruton, 1960; Coleman and Wright, 1975; Galloway, 1975). By the late 1980s, the recognition that estuarine deposits were common components of incised valleys (Dalrymple et al., 1992; Zaitlin et al., 1994) led to the reinterpretation of a number of deltaic and shallow-marine deposits as estuarine, resulting in an explosive increase in the number of papers documenting estuaries in the stratigraphic record (Boyd, 2010). The last ten years have witnessed an increased interest in deltaic sedimentation, with a large number of studies refining our understanding of deltaic models (see Bhattacharya, 2006, 2010, for reviews). Although much emphasis has been placed on the distinction between deltas and estuaries, alternative facies models for marginal-marine systems have been comparatively less explored.

Marginal-marine embayments constitute a common element of the modern world coasts. They represent 15% of the world's coastlines including 3100 km of the east coast of the United States, 1600 km of the east coast of the Gulf of Mexico, 960 km of the east coast of South America, 680 km of the east coast of India, 560 km of the North Sea coast of Europe, 300 km of Eastern Siberia, and 900 km of the North Slope of Alaska (Davis and Fitzgerald, 2004). However, few examples of ancient brackish-water embayments have been documented (e.g., Hubbard et al., 1999; Hayes et al., 1994; Geier and Pemberton, 1994; Desjardins et al., 2009, 2010; Yoshida et al., 2004). This paradox may be attributed to the difficulty in their recognition in the stratigraphic record. Although significant effort has been made since the late sixties to understand the sedimentary facies and the processes that occur in modern marginal-marine embayments (Davis and Fitzgerald, 2004), the diagnostic criteria that may allow recognition of these depositional settings in the stratigraphic record still remain poorly understood.

Integration of ichnological and sedimentological data has revealed that the Upper Devonian–Lower Carboniferous Bakken Formation of subsurface Saskatchewan contains not only open-marine deposits, but also brackish-water marginal-marine facies (Angulo and Buatois, in press). Detailed analysis of these deposits demonstrates that these cannot be interpreted following classic estuarine or deltaic models. Consequently, this unit provides an opportunity to improve our understanding of the complexities associated with facies mosaics in brackish-water marginal-marine settings. From a practical perspective, this approach is timely because the Bakken Formation has become one of the most important hydrocarbon producing units in North America. The aims of this chapter are to: (1) present a detailed description of the sedimentary facies of the brackish-water marginal-marine interval of the Bakken Formation, (2) discuss the different possible palaeoenvironmental interpretations for this interval, (3) present the brackish-water embayment model as the depositional model that better explains the sedimentological and ichnological data, and the sequence-stratigraphic framework of these deposits, and (4) discuss the criteria that allow the recognition of brackish-water marginal-marine embayments in the stratigraphic record.

## 4.2. GEOLOGICAL FRAMEWORK

The Bakken Formation represents a widespread siliciclastic unit which records part of the infill of the Williston Basin during the Late Devonian–Early Carboniferous in southwestern Manitoba, southern Saskatchewan, northeastern Montana and northwestern North Dakota. The study area is located in southeastern Saskatchewan (48° 59'–49° 57' latitude N, 102 16'–105 20' longitude W), covering approximately 29,900 km$^2$. For this study 62 well cores were analysed (Fig. 4.1). In Saskatchewan, the Bakken unconformably overlies the Big Valley and Torquay formations, while it is, in turn, conformably overlain by the Souris Valley Beds (equivalent to the Lodgepole Formation) of the Madison Group (Christopher, 1961; LeFever et al., 1991; Smith et al., 1995; Kohlruss and Nickel, 2009) (Fig. 4.2). Toward the north, in west-central Saskatchewan, the Bakken Formation is truncated by the sub-Mesozoic unconformity (Smith et al., 1995), while toward the west, in Alberta and British Columbia, it is correlated with the Exshaw and Banff formations (MacDonald, 1956).

Hayes (1985) and Karma (1981) showed that the conodont fauna indicates that the Bakken Formation is Late Devonian–Early Carboniferous in age. They agreed that the lower member is Famennian, while the upper member is Kinderhookian. Identification of the Late Devonian–Early Carboniferous boundary is difficult due to the scarcity of conodonts between the shales from the lower and upper members, but it is assumed to be within the middle member.

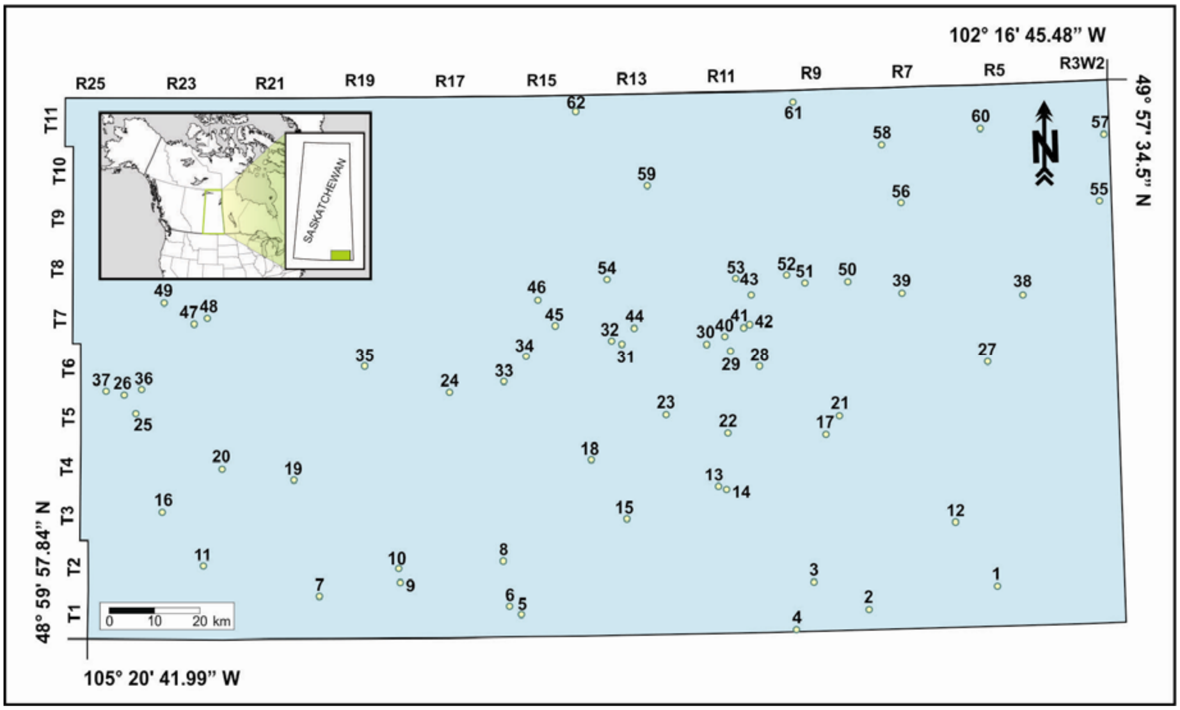



Figure 4.1 – Map showing the study area and location of well cores analyzed for this study (See Chapter 1 for wells ID's).

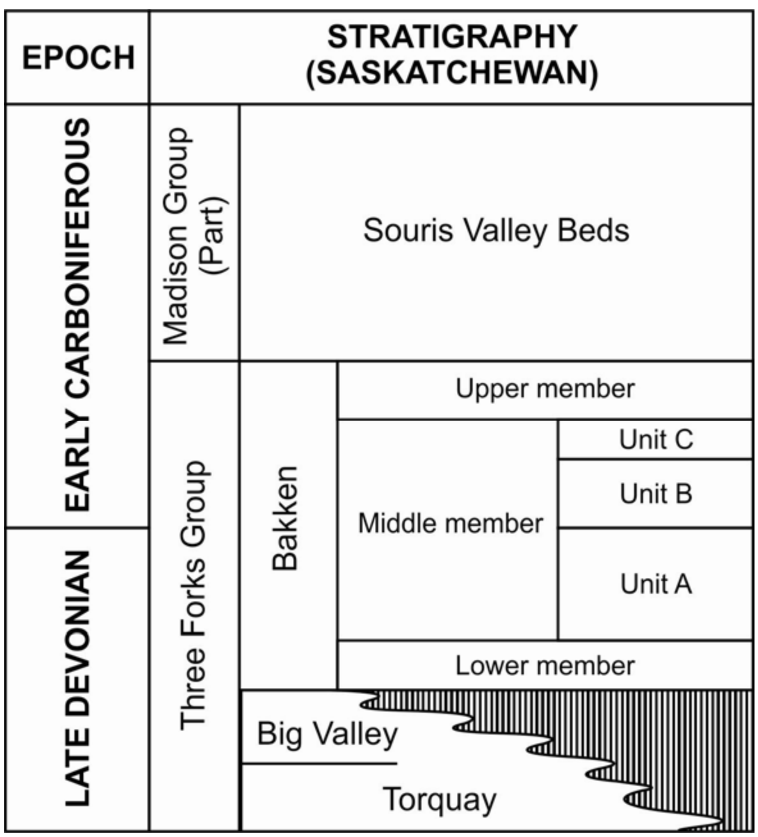



Figure 4.2 – Stratigraphic chart of Saskatchewan for the Late Devonian–Early Carboniferous.

The Bakken Formation is subdivided into three members: lower, middle and upper members. The lower and the upper member are homogeneous, and consist of only one sedimentary facies (black shale) deposited on a shelf, below the storm wave base. The middle member, in contrast, is much more heterogeneous, both vertically and laterally, and comprises several sedimentary facies (calcareous to dolomitic siltstone, very fine- to fine-grained sandstone and interlaminated mudstone, siltstone and very fine-grained sandstone). These facies represent open-marine (lower offshore to lower shoreface) and brackish-water marginal-marine settings. The middle member is, in turn, subdivided into units A, B and C (Fig. 4.3).

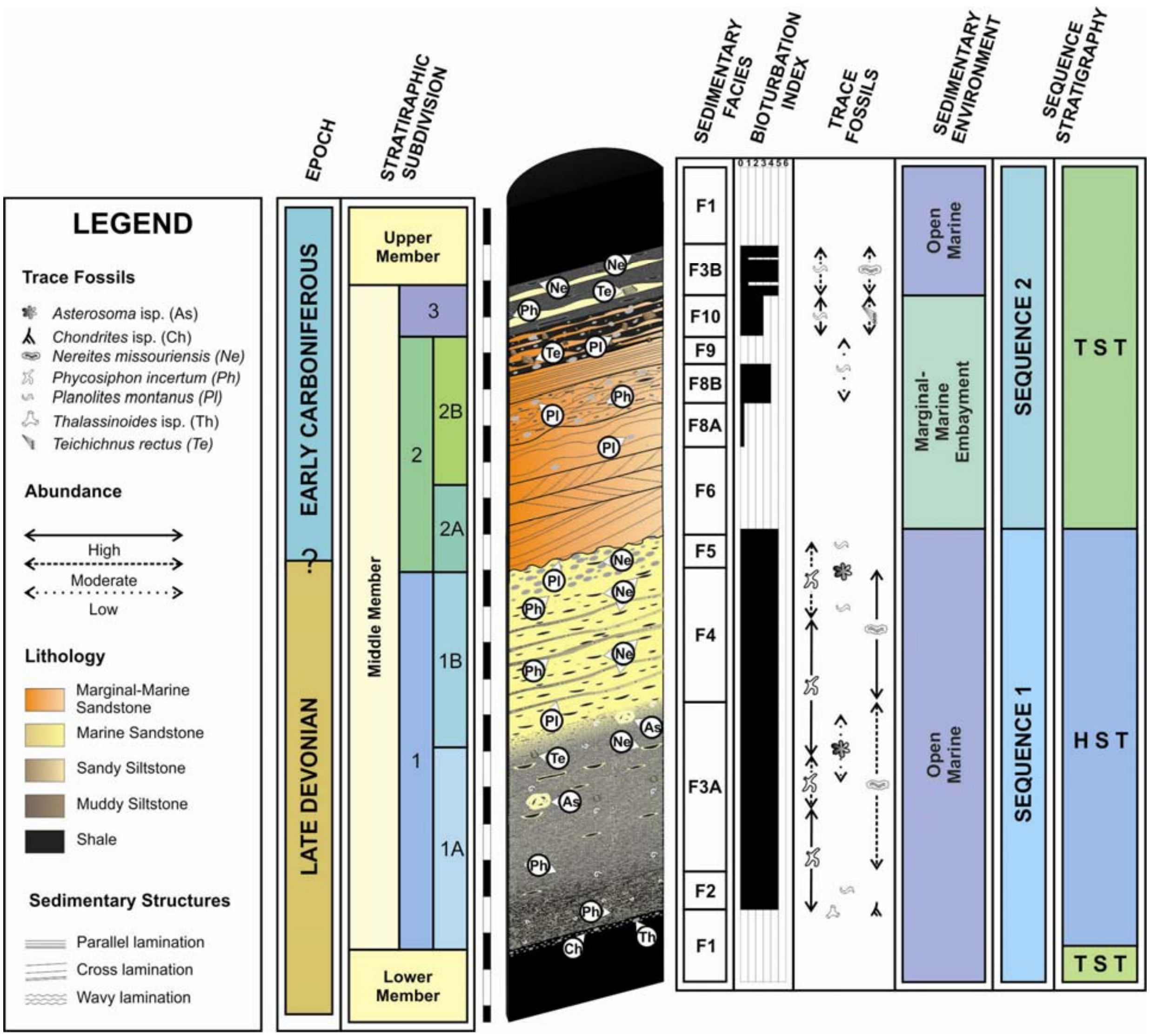



Figure 4.3 – Idealized core log showing the stratigraphic subdivision of the Bakken Formation in southeastern Saskatchewan and its sedimentological and ichnological characteristics, and the interpreted sedimentary environment and sequence stratigraphy. Facies 6 and subfacies 8C are not present in the diagram because, very commonly, where facies 6 is present, these facies are not.

## 4.3. SEDIMENTARY FACIES

Eleven sedimentary facies, based on lithology, sedimentary structures, trace fossils content and bioturbation index, were defined in the Bakken Formation in southeastern Saskatchewan. Of these eleven facies, six (facies 1 to 5, and facies 11) were interpreted as having been deposited under open-marine conditions (lower and upper members, unit A and C of the middle member) and five (facies 6 to 10) as having formed under brackish-water marginal-marine conditions (unit B of the middle member). For estimation of bioturbation index (BI), the Taylor and Goldring (1993) scheme was used. The description of the distribution of the facies is based on isochore maps presented in Angulo and Buatois (2010, in press). Detailed descriptions of the open-marine sedimentary facies are presented in Angulo et al. (2008), and Angulo and Buatois (2009).

### 4.3.1. Facies 6: High-Angle Planar Cross-Stratified Sandstone

Description: Facies 6 consists of light-brownish gray, locally dark gray, well-sorted, high-angle planar cross-stratified, commonly calcareous fine-grained sandstone. Some intervals are massive or present parallel lamination and/or low-angle cross-stratification. Current ripples are rare. Pyrite and oolites ($CaCO_3$) are common. No body and trace fossils are present in this facies (Fig.4.4).

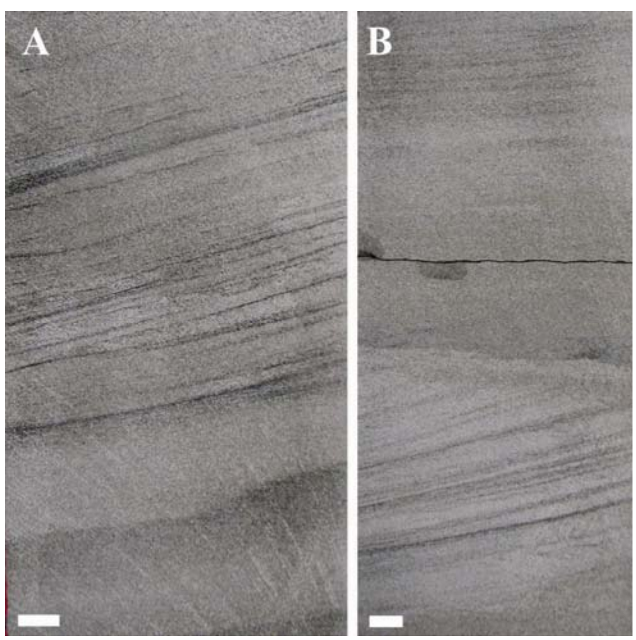



Figure 4.4 – Selected core intervals illustrating facies 6 (barrier-bar deposits). High-angle planar cross-stratified fine-grained sandstone. Some intervals are massive or present low-angle cross lamination. Lack of bioturbation is characteristic. (A) Well 8–11–8–14W2, 1603.04 m. (B) Well 8–11–8–14W2, 1599.55 m. Bar scale = 1 cm.

Distribution: Facies 6 is commonly interfingered with subfacies 8A. Typically, it overlies open-marine deposits of unit A. However, locally it overlies other brackish-water facies, such as facies 9 and subfacies 8A and 8B. In turn, it is overlain by brackish-water deposits, such as subfacies 8A, 8B, facies 9, and very rarely by facies 7. The upper contact is conformable, and it may be gradational or sharp. The basal contact, in contrast, is erosional and sharp, but considered conformable where in contact with underlying brackish-water facies, and unconformable where in contact with open-marine deposits of unit A. In this case, the base of facies 6 is interpreted as a co-planar surface, in which a sequence boundary is amalgamated with a transgressive surface. The upper contact may be gradational or sharp. Facies 6 occurs in the central region of the study area, where it forms a southeast-northwest-trending belt. Its thickness ranges from 0 on the east, west and north, to 5.1 m in the central portion of the study area (Fig. 4.5).

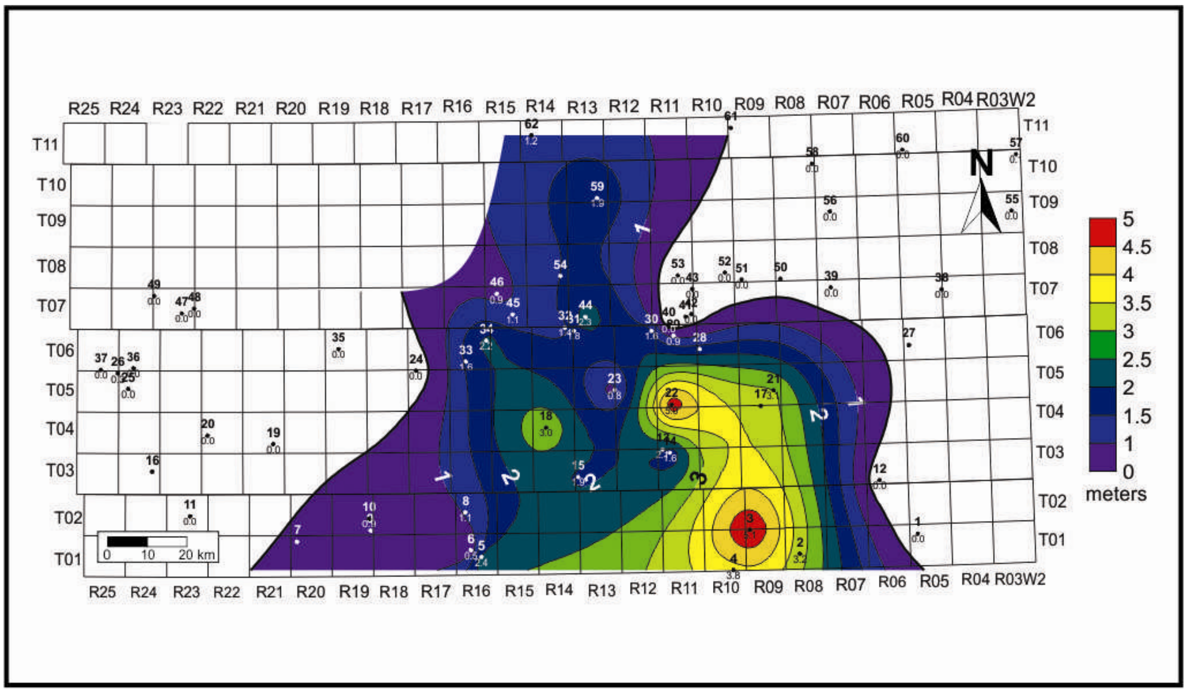



Figure 4.5 – Isochore map of facies 6. Facies 6 occurs in the central region of the study area, where it forms a southeast-northwest trending belt. It thickness varies from 5.1 m. in the southeast-central region to 0 m towards the east and west. After Angulo and Buatois (2010).

Interpretation: The presence of oolites, commonly associated to agitated shallow waters (Flügel, 2004), together with an erosional base, high-angle planar cross-stratification, and reactivation surfaces, are evidence of a high-energy environment. The absence of bioturbation, which contrasts with the underlying open-marine facies, implies stressful conditions, most likely a combination of high-energy levels and brackish-water conditions. Facies 6 is interpreted as a barrier-bar, oriented northwest-southeast, which migrated toward the northeast in the study area as a transgression proceeded (Fig. 4.6).

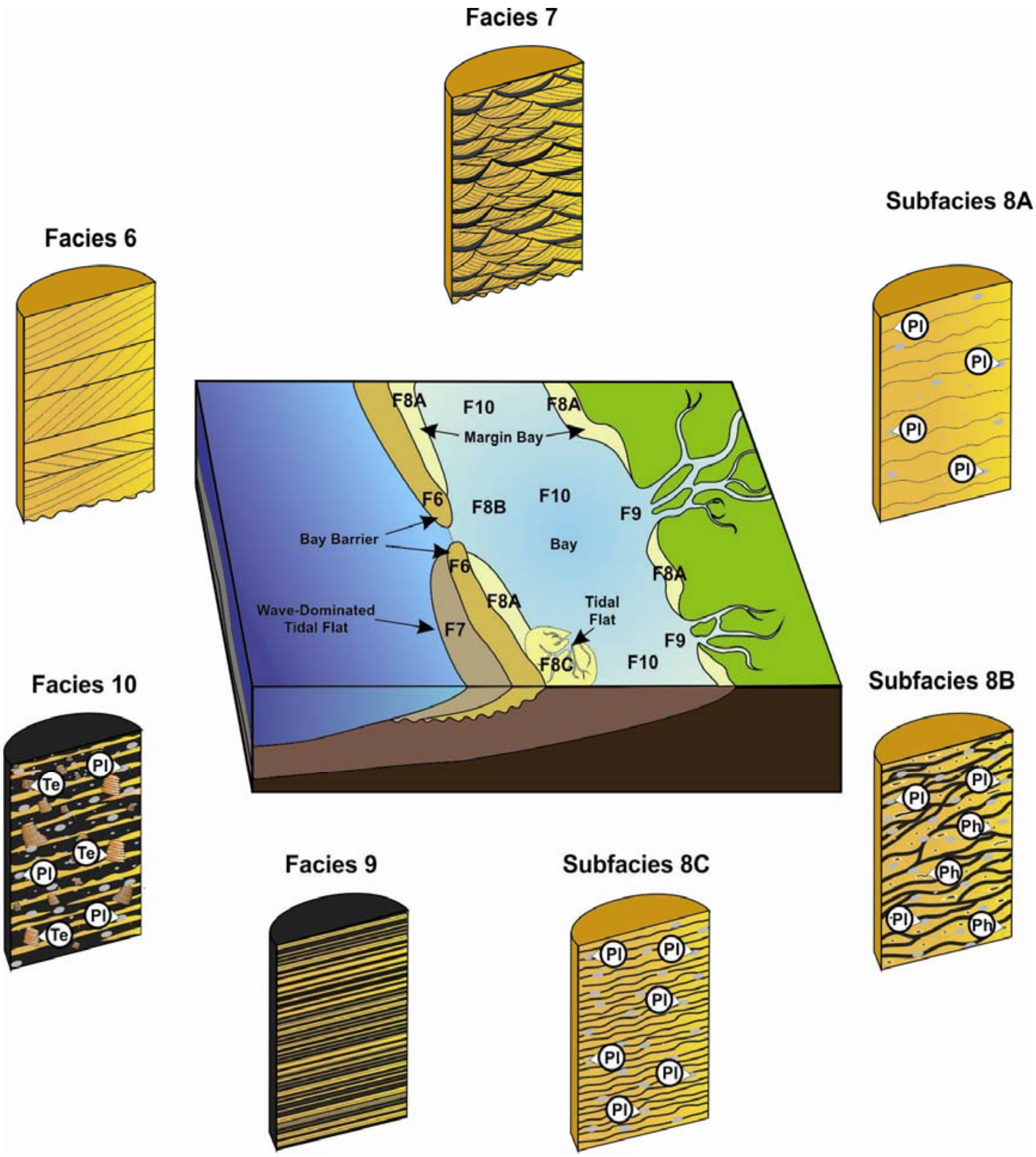



Figure 4.6 – Schematic diagram showing the subenvironments interpreted for the different sedimentary facies within the brackish-water marginal-marine embayment. Facies 6 corresponds to the barrier bar, facies 7 is interpreted as an open coast wave-dominated tidal flat, subfacies 8A is associated to the barrier-bar and margin-bay deposits, subfacies 8B is related to bay deposits with a stronger marine influence, subfacies 8C corresponds to tidal flat in a more protected area within the embayment, facies 9 as margin-bay deposits mostly deposited under freshwater conditions, and facies 10 interpreted as bay deposits with strong brackish-water conditions. Note the lack or low bioturbation degree and the low ichnodiversity that characterized the sedimentary facies. (Te) *Teichichnus rectus*, (Pl) *Planolites montanus*, (Ph) *Phycosiphon incertum*.

### 4.3.2. Facies 7: Flaser-Bedded Sandstone

Description: Facies 7 is composed of light gray to medium gray, flaser-bedded, very fine-grained sandstone. Symmetrical and asymmetrical ripples are common. Bipolar ripple migration directions are observed, although commonly one direction is dominant. Locally, climbing ripples occur. Mudstone drapes (1–8 mm thick) are abundant or moderate, although in some locations they can be moderate to rare. Absence of bioturbation is characteristic (Fig. 4.7).

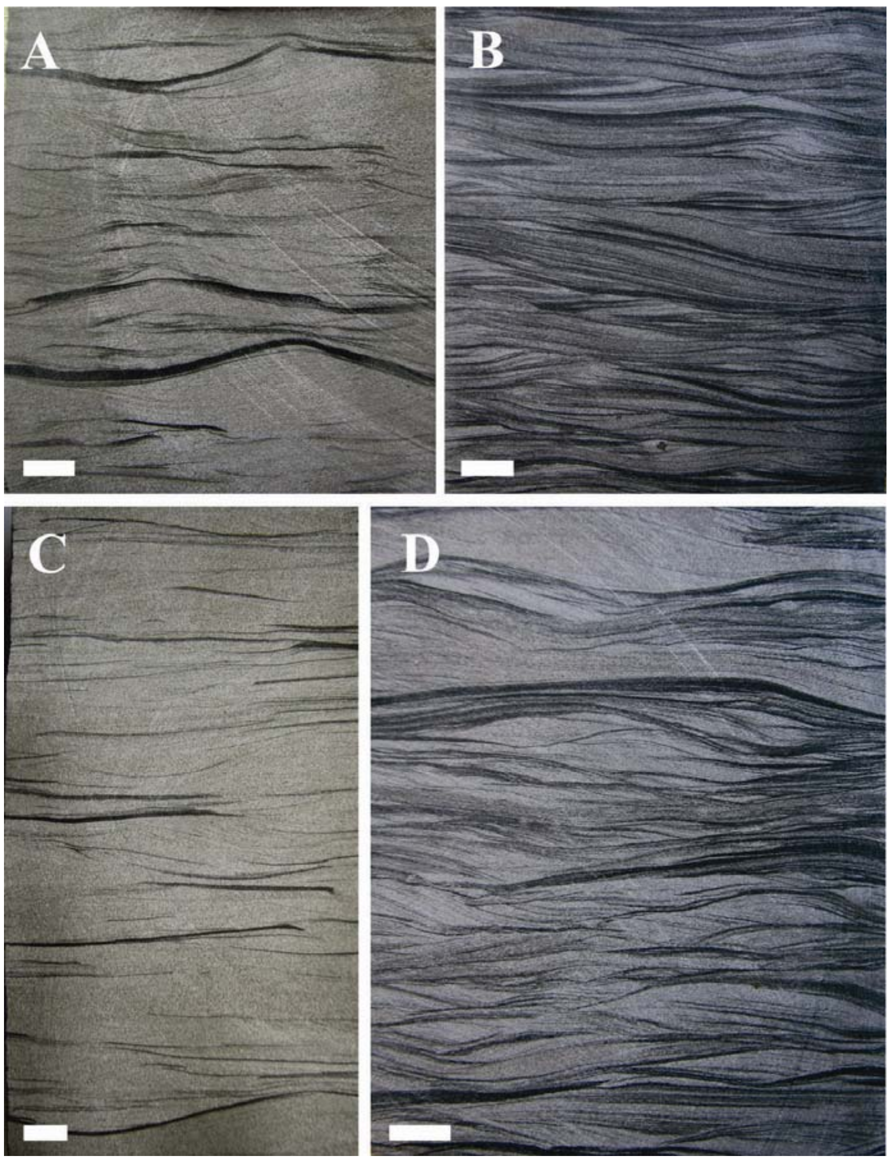



Figure 4.7 –- Selected core intervals illustrating facies 7 (wave-dominated tidal-flat deposits). Flaser bedded very fine-grained sandstone. Note the presence of symmetrical, asymmetrical and climbing ripples. Ratio of sandstone/mudstone varies in different locations. Lack of bioturbation is characteristic. Bar scale = 1 cm. (A) 6–11–4–21W2, 2145.51 m. (B) 6–13–2–19W2, 2727.2 m. (C) 8–23–3–24W2, 2039.88 m. (D) 6–13–2–19W2, 2326.36 m. Bar scale = 1 cm.

Distribution: Facies 7 typically overlies subfacies 8C, although locally overlies other brackish-water facies, such as subfacies 8A and 8B, or very rarely facies 6, 9, 10 or open marine deposits of unit A. This facies is, in turn, commonly overlain by subfacies 8A and 8B or facies 10. Its basal contact is generally sharp and erosional, while its upper contact is commonly gradational or sharp, but without signs of erosion. This facies is restricted to the western region of the study area, reaching up to 3.6 m thick in the southwestern area (Fig. 4.8).

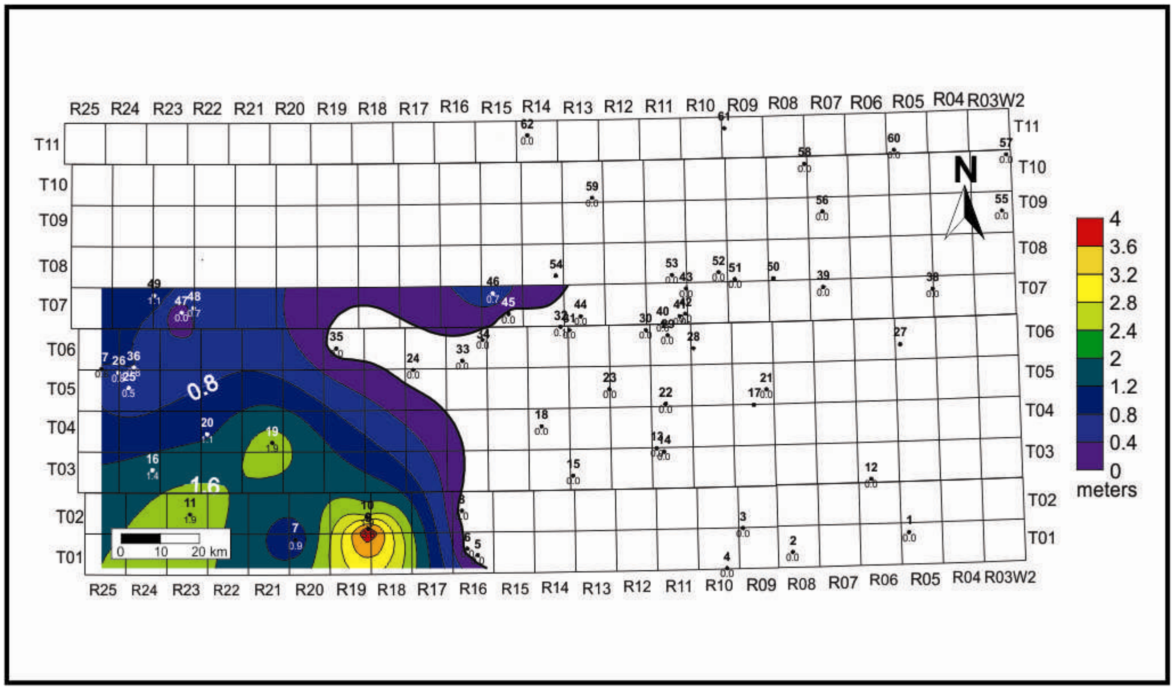



Figure 4.8 – Isochore map of facies 7. Facies 7 is restricted to the southwest portion of the study area. Its thickness varies from 0 to 3.6 m. After Angulo and Buatois (2010).

Interpretation: The presence of flaser bedding with symmetrical and asymmetrical ripples reflecting bipolar ripple migration direction is interpreted as having been produced by a combination of waves and tidal currents in an open coast wave-dominated tidal flat (Fig. 4.6). Significant aggradation rates are evidenced by the presence of climbing ripples (Ashley et al., 1982). Yang et al. (2008) and Fan et al. (2004) described similar modern deposits in Baeksu (southwestern coast of Korea) and Parksville Bay (Vancouver Island, British Columbia, Canada). Potential ancient examples occur in the upper part of the Ordovician Wenchang Formation in Zhejiang Province, China. Facies 7, as well as the deposits from Baeksu and Parksville Bay, are interpreted as open-coast wave-dominated tidal flats. The ichnodiversity and degree of bioturbation of tidal-flat deposits is extremely variable (Mángano and Buatois, 2004; Buatois and Mángano, 2011). In the present case, the absence of bioturbation may reflect overall high-energy conditions.

### 4.3.3. Facies 8: Wavy-Laminated to Bedded Sandstone

Facies 8 comprises light to medium gray, wavy-laminated very fine-grained sandstone with mudstone drapes. This facies has been subdivided into three subfacies: 8A, 8B, and 8C.

#### *4.3.3.1. Subfacies 8A*

Description: Subfacies 8A is composed of light to medium gray, beige and very locally light red, wavy-laminated to bedded, slightly calcareous in places, very fine-grained sandstone. Mudstone drapes and pyrite are common; current ripples and microfaults occur locally. Trace fossils are rare (BI 0–1), and commonly it is difficult to identify discrete ichnotaxa, with the exception of *Planolites montanus* (Fig. 4.9).

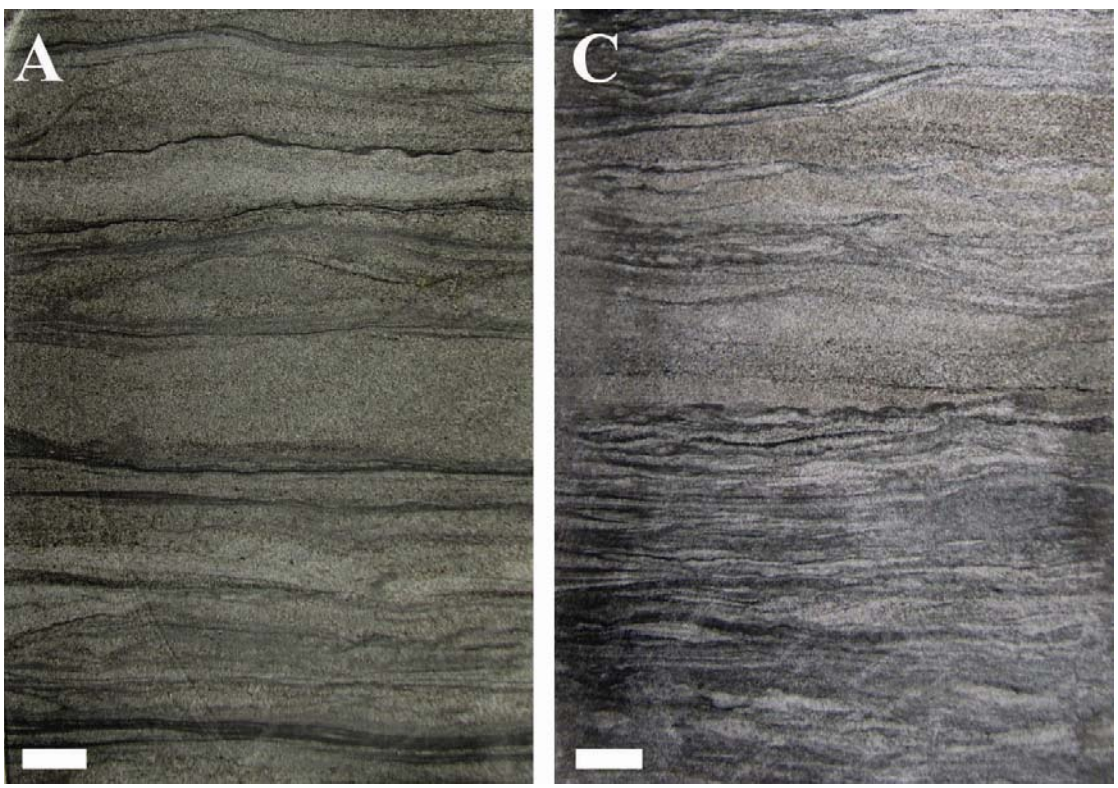



Figure 4.9 – Selected core intervals illustrating subfacies 8A (barrier-bar and marginal-bay deposits). Wavy-laminated to bedded very fine-grained sandstone. Mudstone drapes and low bioturbation are characteristic (A) 16–35–6–14W2, 1709.22 m. (B) 4–2–1–10W2, 2250.88 m. Bar scale = 1 cm.

Distribution: Subfacies 8A commonly interfingers with facies 6, and it commonly overlies open-marine deposits of unit A and facies 9, although it may also overlie facies 7 and subfacies 8B. This subfacies is, in turn, generally overlain by facies 9, 10 and subfacies 8B. Both, the lower and upper contact may be gradational or sharp. Subfacies 8A is widely distributed, covering the entire study area with exception of some restricted locations (central-west and northeast). Its thickness varies from 0 to 2.6 m (Fig. 4.10).

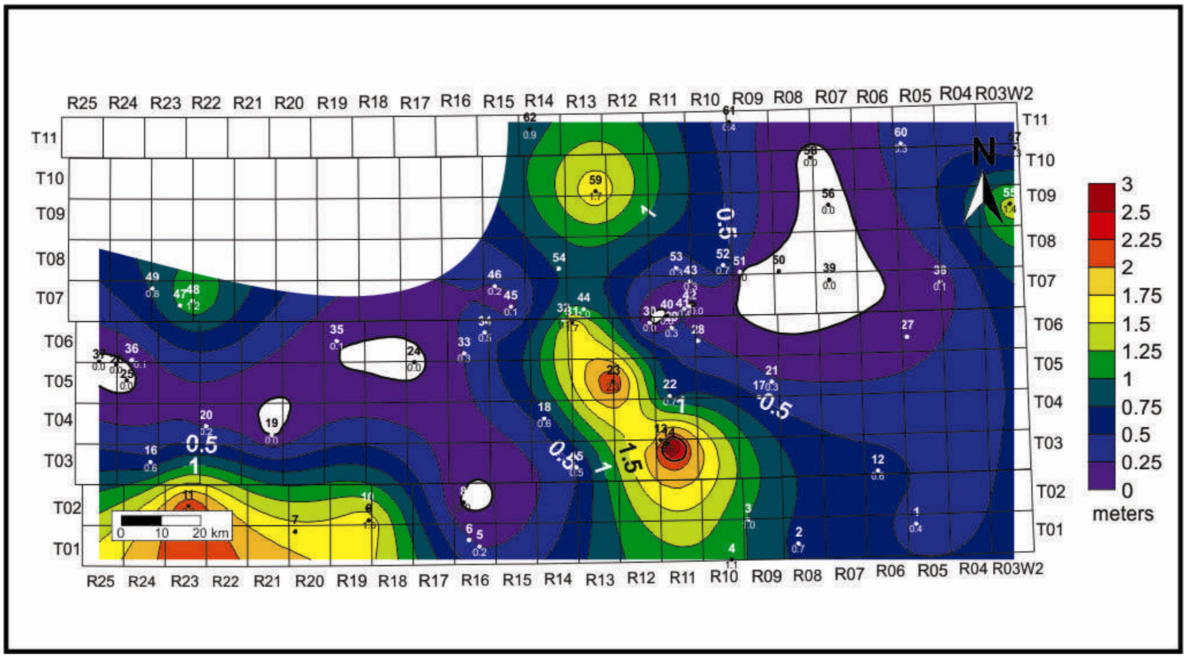



Figure 4.10 – Isochore map of subfacies 8A. Subfacies 8A is regionally distributed, absent locally in the west-central and northeastern portion of the study area. Its thickness varies from 0 to 2.6 m. After Angulo and Buatois (2010).

Interpretation: Low bioturbation degree and ichnodiversity indicate stressful conditions. The presence of mudstone drapes alternating with sandstone-dominated intervals reflects fluctuations in energy conditions. This facies likely reflects lower-energy conditions characteristic of the back-barrier bar (where interfingered with the latter) or proximal deposits along the margins of the embayment (Fig. 4.6).

*4.3.3.2. Subfacies 8B*

Description: Subfacies 8B is composed of light, very fine-grained sandstone with common dark gray shale laminae, rarely calcareous; locally mud clasts occur (< 5 mm). Common irregular shale laminations and soft-sediment deformation structures (e.g., convolute bedding) occur.

Locally, microfaults are also present. The bioturbation index varies from 3 to 4, in which a burrow mottled texture is characteristic. Dominant elements include *Planolites montanus* and *Phycosiphon incertum,* while rare elements are *Nereites missouriensis,* and *Teichichnus rectus* (Fig. 4.11).

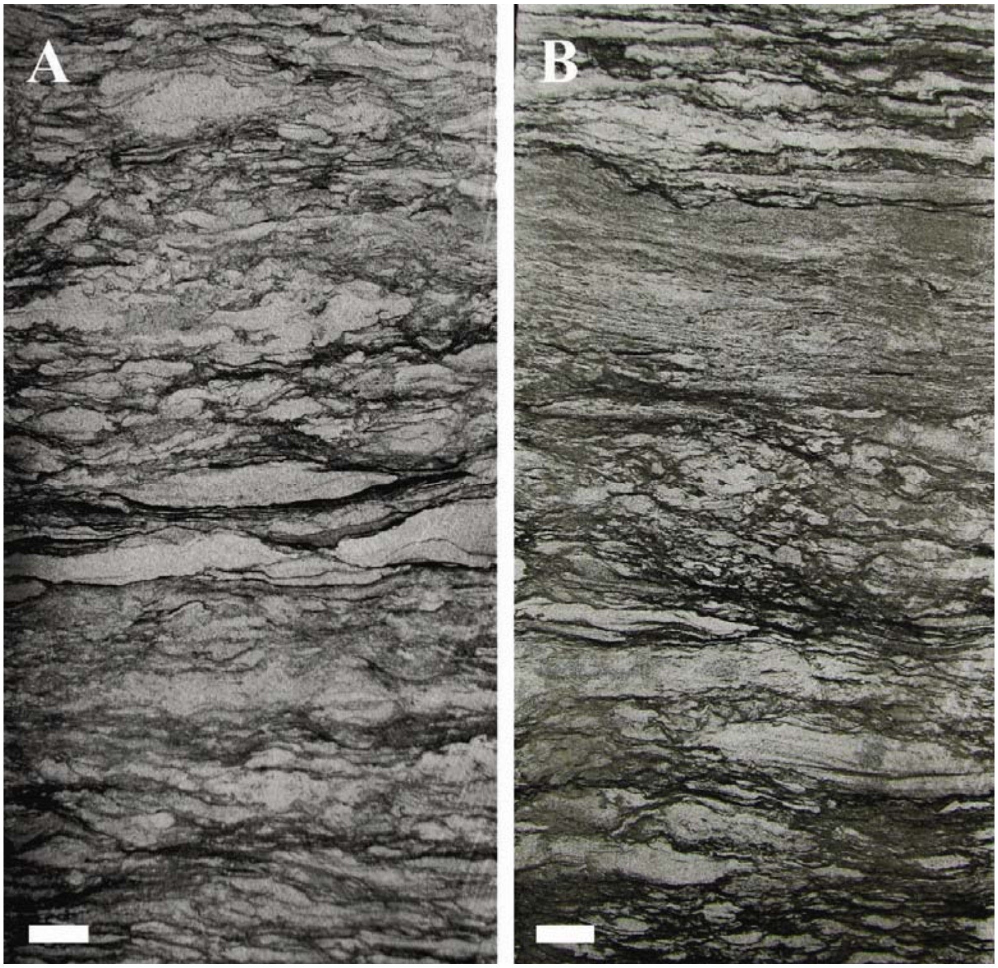



Figure 4.11 – Selected core intervals illustrating subfacies 8B (distal-bay deposits reflecting a stronger marine influence). Note moderate to high bioturbation. Typical marine ichnofossils, such as *Phycosiphon incertum* are present (A) 8–23–3–24W2, 2038.64 m. (B) 1–20–6–19W2, 1932.38 m. Bar scale = 1 cm.

Distribution: Subfacies 8B commonly interfingers with subfacies 8A and facies 9, although it locally overlies facies 6 or 7. Both the lower and upper contacts may be gradational or sharp. This facies has a wide distribution covering the south, west-central and northeast portion of the study area, ranging in thickness from 0 to 1.9 m (Fig. 4.12).

Interpretation: Subfacies 8B is interpreted as a bay deposit (Fig. 4.6). However, although ichnological evidence reflects brackish-water conditions, the moderate bioturbation and the presence of *Phycosiphon incertum* and *Nereites missouriensis* suggest a marine influence reflecting a major connection to the open sea. Locally, high sedimentation rates are interpreted based on the presence of synsedimentary deformational structures.

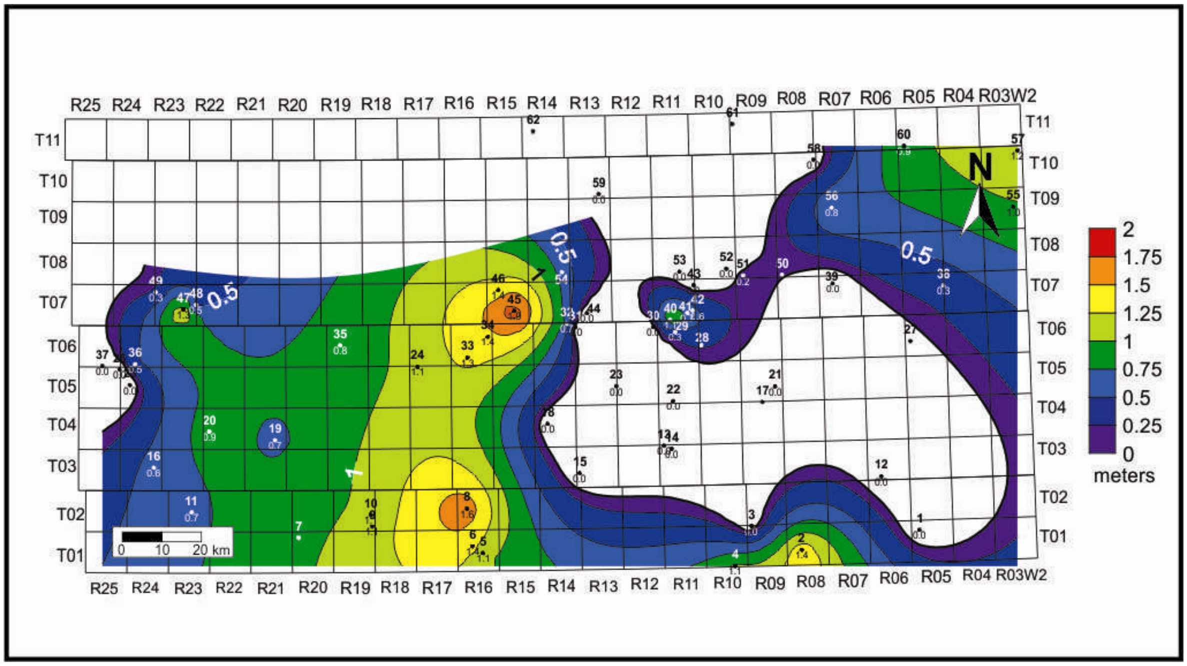


Figure 4.12 – Isochore map of subfacies 8B. Subfacies 8B shows a fairly regional distribution, being absent in the central-east portion of the study area. Its thickness ranges from 0 to 1.9 m. After Angulo and Buatois (2010).

*4.3.3.3. Subfacies 8C*

Description: Subfacies 8C comprises regular alternations of light gray very fine-grained sandstone and mudstone laminae (< 3 mm thick). Locally inclined heterolithic stratification and root trace fossils are present. The bioturbation index ranges from 2 to 3. The only trace fossil recorded is *Planolites montanus* (Fig. 4.13).

Distribution: Subfacies 8C typically overlies open-marine deposits of unit A, or facies 9, and it is, in turn, commonly overlain by facies 7. The lower contact is gradational or sharp but without evidence of erosion, while the upper contact is generally erosional. It is restricted to the southwestern portion of the study area, with a thickness ranging from 0 to 4.4 m (Fig. 4.14).

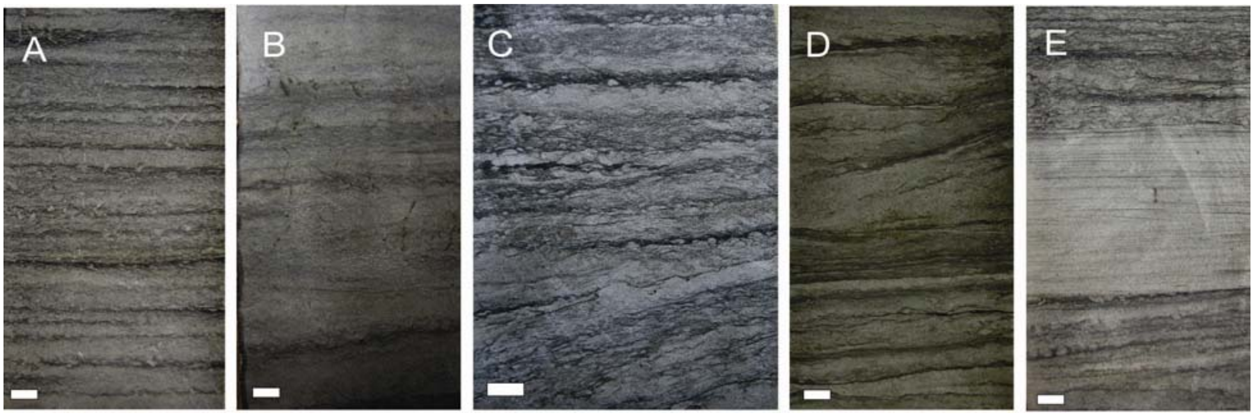



Figure 4.13 – Selected core intervals illustrating subfacies 8C (tidal-flat deposits). Alternated very fine-grained sandstone and mudstone laminae characterized these deposits. Note the low bioturbation degrees, being *Planolites montanus* the only trace-fossil recognized. In photos (C) and (D) heterolithic inclined stratification is observed, while root traces are present in (B), and parallel-laminated sandstone interpreted as a tempestite is observed in E (A) 14–15–2–23W2, 2151.5 m. (B) 8–23–3–24W2, 2040.75 m. (C) 9–18–4–22W2, 2045.29 m. (D) 8–23–3–24W2, 2043.58 m. (E) 14–15–2–23W2, 2151.9 m. Bar scale = 1 cm.

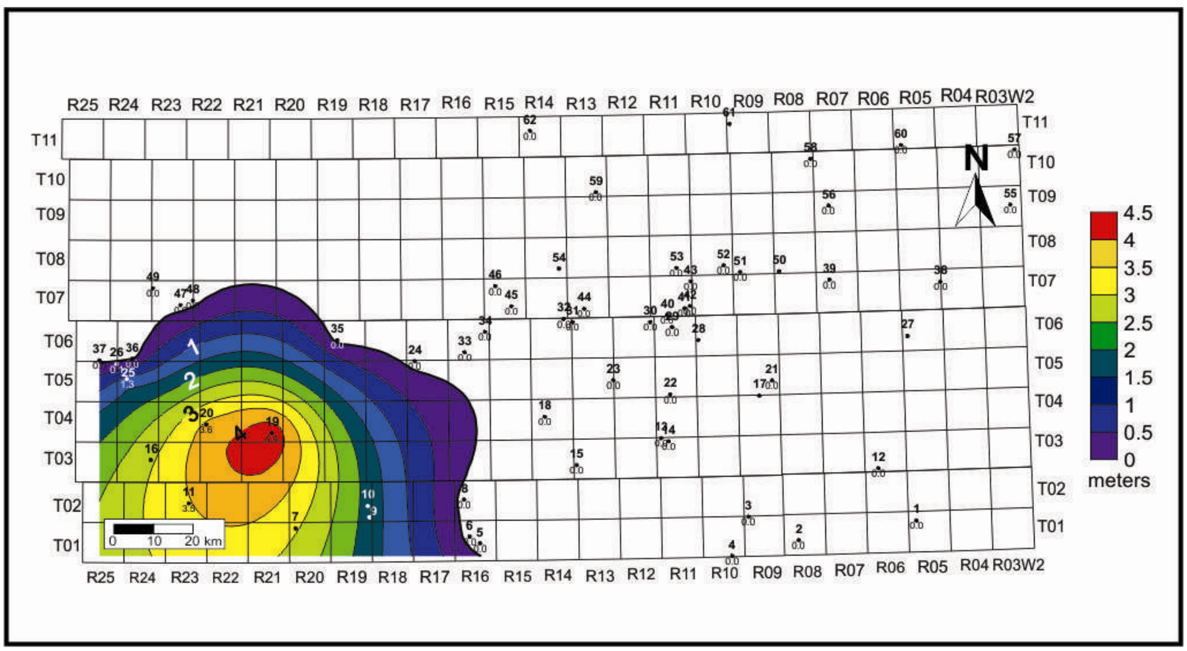



Figure 4.14 – Isochore map of subfacies 8C. Subfacies 8C is restricted to the southwestern portion of the study area. Its thickness varies from 0 to 4.4 m. After Angulo and Buatois (2010).

Interpretation: The regular intercalation of very fine-grained sandstone and mudstone laminae resembles tidal rhythmites (e.g., Kvale et al., 1989; Lanier, 1993). Although no statistical cyclicity analysis has been performed to support this interpretation, the remarkable regularity of the sedimentary fabric and the overall depositional setting is consistent with tidally influenced sedimentation. The local presence of roots records waterlogged paleosols along the margins of the embayment. Intervals with inclined heterolithic stratification are interpreted as being formed by the migration of tidal channels and creeks in the intertidal zones (Thomas et al., 1987) (Fig. 4.6). Integration of ichnologic and sedimentologic characteristics suggest that this subfacies may record deposition in proximal zones along the margins of the embayment under strong tidal influence.

### 4.3.4. Facies 9: Thinly Interlaminated Sandstone and Siltstone

Description: Facies 9 is composed of very thinly laminated gray, very fine-grained sandstone and dark gray muddy siltstone, both locally calcareous. Parallel lamination, current-ripple cross-lamination and mudstone drapes occur. Very rarely root trace fossils are present. The bioturbation index ranges from 0 to 1 comprising monogeneric suites of *Planolites montanus* (Fig. 4.15).

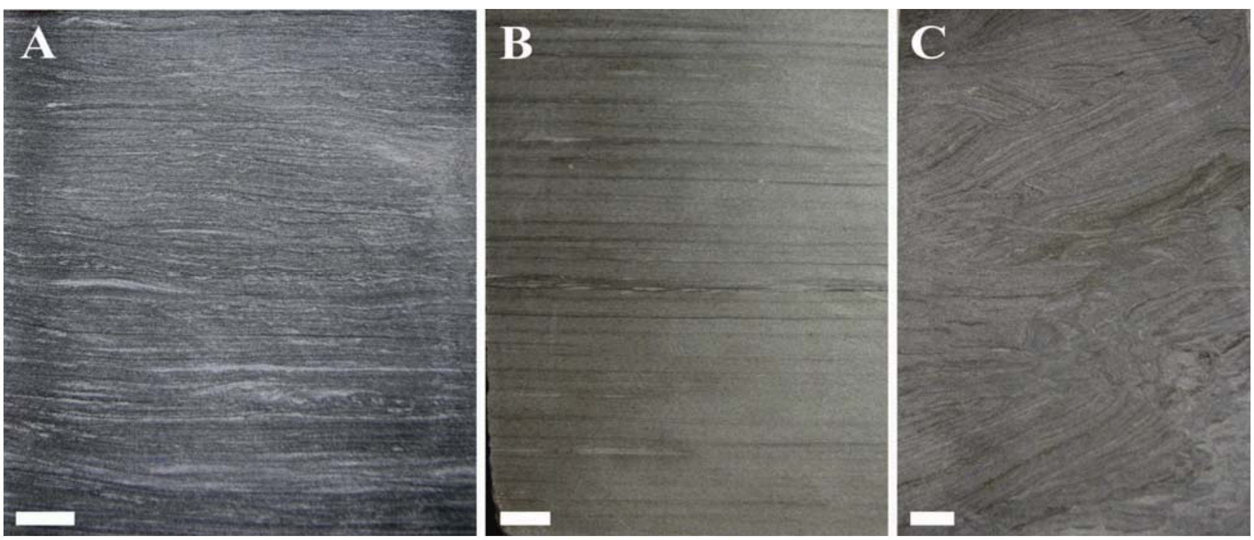



Figure 4.15 – Selected core intervals illustrating facies 9 (marginal-bay deposits). Thinly laminated sandstone and siltstone. Lack of bioturbation is common. Note synsedimentary deformation in (C). (A) 12–21–1–16W2, 2336.55 m. (B) 1–31–1–20W2, 2184.82 m. (C) 15–29–7–15W2, 1707.9 m. Bar scale = 1 cm.

Distribution: Facies 9 may interfinger with subfacies 8A, or more rarely subfacies 8B. Commonly, it overlies the two latter subfacies, and rarely open-marine deposits of unit A or facies 6; while is generally overlain by facies 10, subfacies 8A and 8B, rarely open-facies of unit C. Both, the lower and upper contact may be gradational or sharp. This facies is characterized by a wide distribution which covers the entire study area with the exception of the most western portion and the central-east region of the study area. Its thickness varies from 0 to 2.7 m (Fig. 4.16).

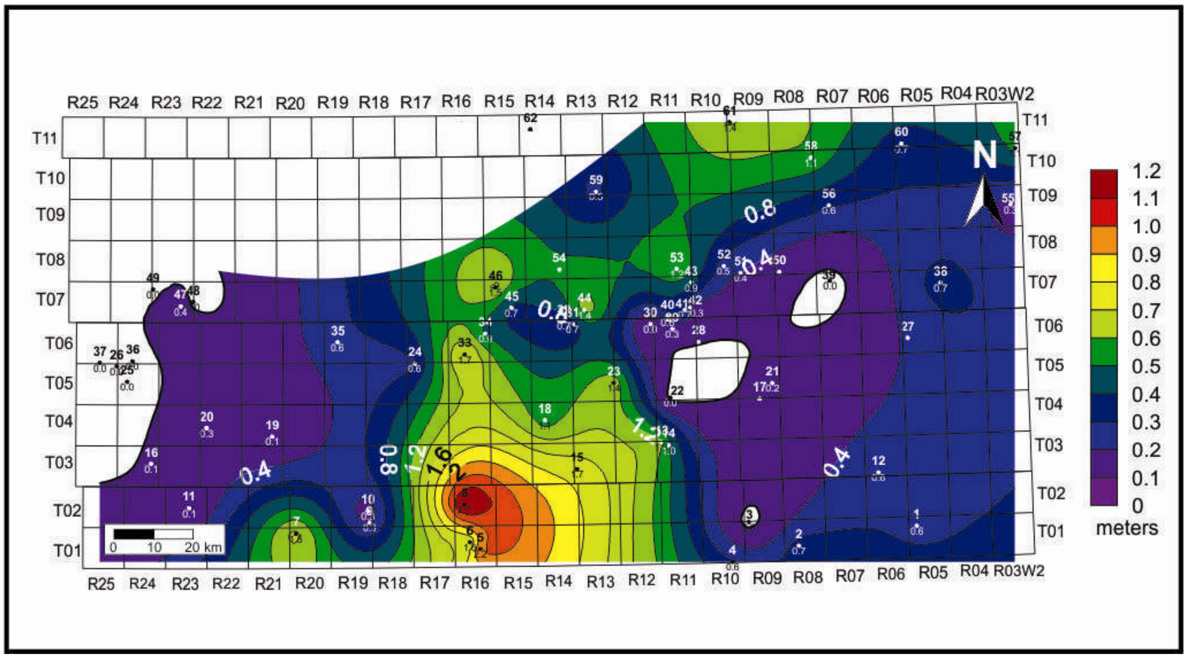



Figure 4.16 – Isochore map of facies 9. Facies 9 displays a fairly regional distribution, being only absent in the west and central-east portion of the study area. Its thickness ranges from 0 to 2.7 m. After Angulo and Buatois (2010).

Interpretation: Interlaminated sandstone and muddy siltstone represent constant fluctuations in energy conditions most likely due to tidal influence during deposition of this facies. The very low bioturbation and ichnodiversity suggest a highly stressed setting characterized by extreme brackish-water (i.e., oligohaline) to perhaps even freshwater conditions (e.g., Buatois et al., 1997; Mángano and Buatois, 2004). This facies is interpreted as having formed in proximal margins of the embayment, most likely close to the mouth of a fluvial or distributary channel (Fig. 4.6).

### 4.3.5. Facies 10: Thinly Interlaminated Mudstone and Sandstone

Description: Facies 10 is composed of very thinly interlaminated, dark gray, mudstone and light gray, very fine-grained silty sandstone. Parallel-lamination and current ripples are locally present in the sandstone beds. Syneresis cracks and sandstone lenses are also present. The bioturbation index is 3 to 4, with the dominant ichnofauna consisting of *Planolites montanus* and *Teichichnus rectus*, and *Rosselia* isp., *Thalassinoides* isp. and *Siphonichnus eccaensis* as rare elements. Monospecific suites of *Planolites montanus* or *Teichichnus rectus* occur locally (Fig. 4.17).

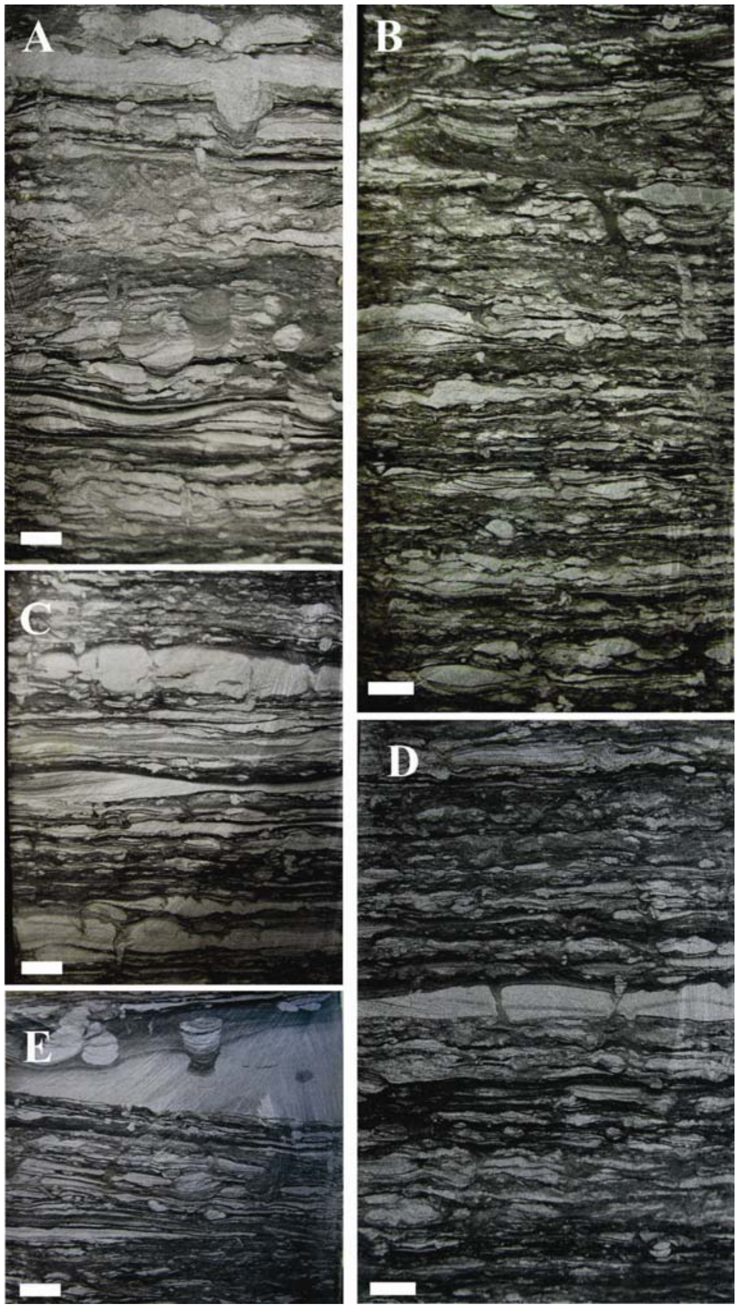



Figure 4.17 – Distal-bay deposits. Thinly interlaminated mudstone and very fine-grained sandstone. Note the presence of current ripples and syneresis cracks. Bioturbation index is commonly moderate, which *Planolites montanus* and *Teichichnus rectus* as dominant elements (A) 8–23–3–24W2, 2036.37 m. (B) 3–18–3–13W2, 2058.66 m. (C) 3–36–6–25W2, 1836.2 m. (D) 9–36–5–25W2, 1818.6 m. (E) 6–13–2–19W2, 2321.43 m. Bar scale = 1 cm.

Distribution: Facies 10 commonly overlies facies 7, 8 or 9, and in turn, overlain by a transgressive lag or other open-marine deposits of unit C. The basal and upper contacts of facies 10 are gradational or sharp but without evidence of erosion. However, where is overlain by the transgressive lag from unit C, the contact is clearly erosional.  With the exception of two localized areas (central and northeast region), facies 10 covers the entire study area, forming up to 4.3 m intervals (Fig. 4.18).

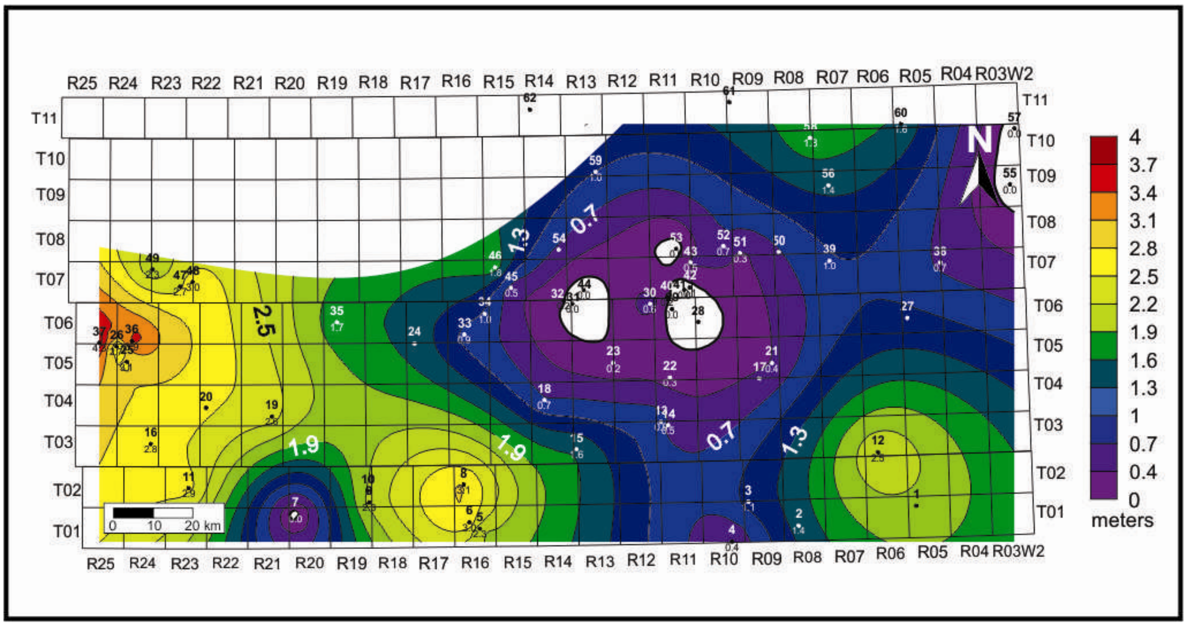



Figure 4.18 – Isochore map of facies 10. Facies 10 displays a fairly regional distribution, being only absent in the central and northeastern portion of the study area. Its thickness ranges from 0 to 4.3 m. After Angulo and Buatois (2010).

Interpretation: The low ichnodiversity, the mudstone drapes, and the regular alternation of mudstone and very fine-grained sandstone layers indicate fluctuations in energy conditions. The high mud content suggests deposition in a more protected and restricted area within the embayment (distal bay), under stressful salinity conditions (Fig. 4.6). The presence of syneresis cracks, which has been related to fluctuations in salinity (Plummer and Gostin, 1981), supports this idea. The sandstone beds with thin parallel lamination are interpreted as storm deposits within the bay.

## 4.4. BRACKISH-WATER NATURE OF UNIT B OF THE BAKKEN MIDDLE MEMBER

Discrimination of brackish-water successions requires comparison with open-marine deposits of the same basin (Buatois et al., 2005; MacEachern and Gingras, 2007). As such, the

Bakken Formation is an excellent example, in which open-marine and brackish-water ichnofauna can be both compared in the same stratigraphic unit. Brackish-water marginal-marine deposits (unit B) are characterized by a low bioturbation index, relatively low ichnodiversity, and the “impoverished” *Cruziana* ichnofacies. In contrast, with the exception of the black shale of the lower and upper members, which are essentially unbioturbated, intervals formed under open-marine conditions (unit A and C) are characterized by a high bioturbation index, moderate ichnodiversity, and the “distal” *Cruziana* ichnofacies.

As noted by Pemberton and Wightman (1992) and Pemberton et al. (2001), bioturbation of brackish-water deposits is characterized by: (1) low diversity; (2) forms typically found in marine environments; (3) simple structures constructed by tropic generalists; (4) suites that are commonly dominated by a single ichnogenus; (5) vertical and horizontal ichnofossils that are common to both the *Skolithos* and *Cruziana* ichnofacies; (6) abundance of some ichnotaxa; (7) presence of monospecific suites; and (8) diminished size compared to fully marine counterparts. The ichnofauna from unit B essentially displays all these diagnostic features, revealing deposition under brackish-water conditions (Angulo and Buatois, 2012). A drastic drop in bioturbation index and ichnodiversity characterizes these deposits when compared with the underlying (unit A) and overlying (unit C) open-marine Bakken deposits. The presence of unbioturbated facies or facies with low bioturbation index (BI 0–3) is common (facies 6, 7, 9, subfacies 8A and 8C). However, moderate bioturbation (BI 3–4) may be present as well in some deposits (subfacies 8B, and facies 10). The ichnodiversity is also typically low; monospecific suites of *Planolites montanus* are very common (subfacies 8A, 8C, facies 9, and locally facies 10), while facies 10 is typically bioturbated only by *Planolites montanus* and *Teichichnus rectus*. Nevertheless, subfacies 8B and locally facies 9 record a more diverse ichnofauna, including not only *Planolites montanus* and *Teichichnus rectus*, but also *Thalassinoides* isp., *Rosselia* isp., *Siphonichnus eccaensis* (facies 10), and *Phycosiphon incertum*. More rarely, *Nereites missouriensis* is present also (subfacies 8B).

Presence of sedimentary structures reflecting tidal influence, such as mudstone drapes, flaser bedding, and regularly interlaminated siltstone, mudstone and very fine-grained sandstone, is also consistent with a brackish-water restricted setting because embayed areas commonly concentrates the tidal energy (Dalrymple, 2010). The existence of syneresis cracks, which have been related to loss of water from the sediment induced by variations in salinity (Plummer and Gostin, 1981), suggests brackish-water conditions during deposition of unit B.

## 4.5. SEQUENCE STRATIGRAPHY OF THE BAKKEN FORMATION: SURFACES AND SYSTEMS TRACTS

In spite of being relatively thin (approximately 30 m in the study area), the Bakken Formation records a complex depositional history, involving several relative sea-level changes and a wide range in depositional settings from shelf to marginal-marine environments. The sequence-stratigraphic framework of the Bakken Formation consists of: (1) a lower transgressive systems tract, (2) a highstand systems tract and (3) an upper transgressive systems tract (Angulo and Buatois, in press) (Fig. 4.3).

### 4.5.1. Acadian Unconformity

During the Late Devonian, most of the Williston Basin and eastern cratonic platform, with exception of the relatively deeper center of the Williston basin and the Prophet trough, were exposed to erosion and reworking due to a sea-level drop, forming the Acadian unconformity (Smith and Bustin, 2000).

### 4.5.2. Lower Transgressive Systems Tract

The lower transgressive systems tract overlies the Acadian unconformity. As the sea-level rose near the end of the Late Devonian (Johnson et al., 1985), a transgression occurred converting much of the North America Craton into a shallow epicontinental sea, where marine black shales from the lower part of the lower member were deposited throughout a series of silled intracratonic basins, below the storm-wave base (Smith and Bustin, 1998; Algeo et al., 2007).

### 4.5.3. Highstand Systems Tract

The lower transgressive deposits gradually passed into highstand deposits as the sedimentation rate exceeded the creation of accommodation space. A southwest progradation of the shoreline took place, as reflected by the stratigraphic succession of shelf black shale from the upper part of the lower member, and lower/upper offshore, offshore transition, and lower shoreface deposits from the middle member (unit A). The most proximal highstand deposits (upper-shoreface, foreshore and backshore deposits) were likely present in the northeast of the study area, but were later cannibalized by erosion resulting from a subsequent sea-level drop.

### 4.5.4. Sequence Boundary between Units A and B

The Late Devonian–Early Carboniferous boundary is placed within the middle member, between unit A and B (Fig. 4.19). This contact is interpreted as a co-planar surface, corresponding to a sequence boundary amalgamated with a transgressive surface (Angulo et al., 2008; Angulo and Buatois, in press), and can be related to the eustatic sea-level fall that was produced by the Devonian Southern Hemisphere glaciation reported by Sandberg et al. (2002).

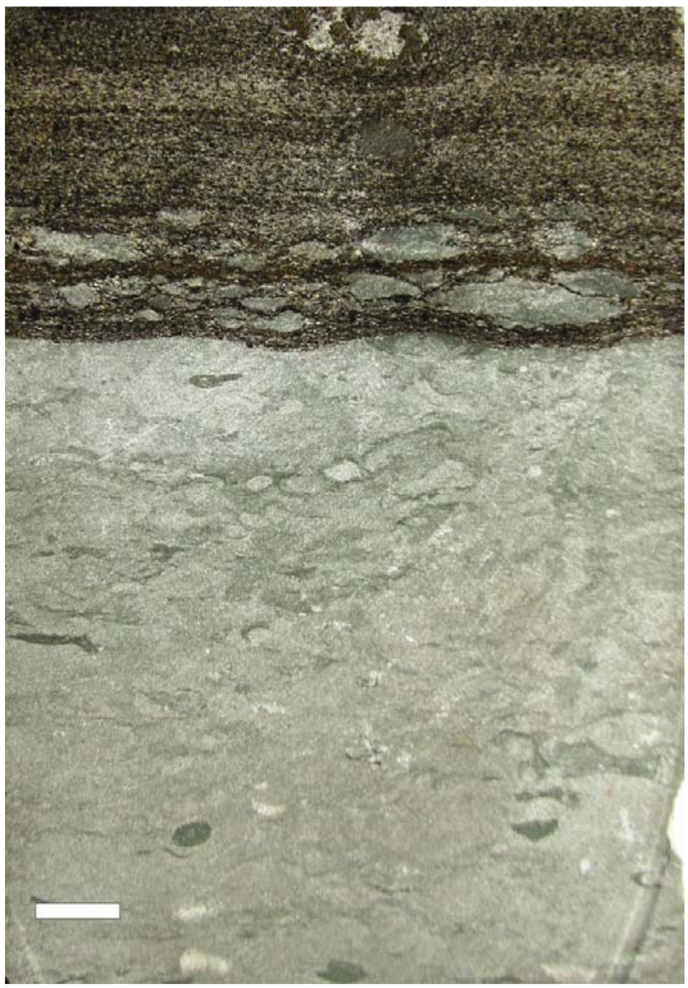


Figure 4.19 – Sequence boundary between unit A and B of the middle member of the Bakken Formation. Note not only the erosive nature of the contact but the sandstone intraclast from the underlying open-marine deposits, indicating that these were consolidated by the time of deposition of the overlying brackish-water deposits, revealing a hiatus between the two facies. Bar scale = 1 cm.

The absence of forced-regressive or lowstand deposits in the study area is attributed to by-pass, or erosion during the subsequent transgression. Evidence of the unconformable nature of this contact is: (1) the sharp and erosive character of the contact, (2) the facies jump between the underlying open-marine deposits (offshore-transition to lower-shoreface deposits from unit A) and the overlying brackish-water marginal-marine deposits (unit B), and (3) the presence of sandstone intraclasts from the underlying open-marine deposits mantling the erosive contact, indicating that these marine deposits were consolidated at the time of deposition of the overlying brackish-water deposits (Fig. 4.19).

### 4.5.5. Upper Transgressive Systems Tract

As the sea-level began rising, deposition in the study area resumed and brackish-water marginal-marine deposits were formed (unit B). As the transgression continued, fully marine conditions were re-established in the entire area. Locally a transgressive lag was deposited in the southeastern region of the study area. Above this lag, offshore deposits (unit C) mantled the whole region, and as the transgression continued, black-shale shelf deposits of the upper member were deposited basinwide.

## 4.6. DISCUSSION

### 4.6.1. Depositional Setting for Unit B of the Middle Bakken

There are three competing models to explain the brackish-water and tidal nature of unit B of the Bakken middle member: deltaic, estuarine, and embayment.

#### *4.6.1.1. Deltaic Interpretation*

Deltas are fundamentally regressive and are characterized by the development of upward-shallowing vertical facies successions (parasequences), which tend to stack forming progradational parasequence sets (Bhattacharya, 2010; Buatois and Mángano, 2011). In siliciclastic settings, deltas are typically related to normal regressions (associated to lowstand and highstand systems tracts) or forced regressions (Catuneanu, 2006). The progradation of a delta forms broadly lobate sediment bodies that internally record a coarsening-upward facies succession, as delta-front sands prograde over more distal prodelta muds (Bhattacharya, 2010).

Sedimentological and sequence-stratigraphic features of unit B of the Bakken brackish-water marginal-marine deposits cannot be explained using a deltaic model. First, deposits from this interval neither record these upward-shallowing vertical facies successions nor the typical progradational stacking pattern of deltaic successions. On the contrary, the general stacking pattern for these deposits is transgressive, passing upward into open-marine deposits. Second, although a regressive trend is recognized with more proximal marginal-marine deposits (unit B) overlying more distal open-marine deposits (unit A), the contact between these units is unconformable, arguing against a normal progradation, in which prodelta deposits are covered by delta-front deposits. Additionally, ichnological characteristics of unit A record high and steady bioturbation, reflecting open-marine conditions, and no evidence of stressful conditions due to variations in salinity, which is typical of deltaic environments, is found in these deposits. Third, distributary channels, or distributary-mouth bars, common elements of delta plains and delta fronts, respectively, are not recognized within the brackish-water deposits of unit B.

#### *4.6.1.2. Estuarine Interpretation*

Estuaries were defined by Dalrymple et al (1992) as “the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes”. These incised valley systems were formed due to erosion during relative sea-level fall and subsequently drowned during relative sea-level rise. Subsequently, Dalrymple (2006) modified the definition of estuaries removing the original reference to drowned valleys as follows: “an estuary is a transgressive coastal environment at the mouth of a river, that receives sediment from both fluvial and marine sources, and that contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth”. In any case, estuaries are typically common elements of transgressive coasts, regardless of the presence of an incised valley (Boyd, 2010).

In the case of the Bakken Formation, the presence of a sequence boundary at the base of the marginal-marine interval would be consistent with an incised valley filled with estuarine deposits. However, given the orientation and dimensions of the depositional bodies and the distribution of the sedimentary facies, the estuarine interpretation is untenable. A regular shoreline oriented southeast-northwest, located farther northeast of the study area during deposition of the underlying open-marine succession (lower member, unit A of the middle member) is interpreted based on the analysis and distribution of the facies. Furthermore, in accordance with the distribution of the brackish-water marginal-marine facies showed by isochore facies maps (Angulo and Buatois, 2010), the incised valley interpreted in the estuary model would be oriented parallel to the old shoreline and would have more than 60 km wide and less than 11 m thick, having a width/thickness ratio of 5454, which notably differs from incised-valley dimensions reported in the geological record by Reynolds (1999) and Gibling (2006). Based on quantitative data collected from the stratigraphic record, these authors noted that the width of incised-valleys ranges between 500 m and 6.3 km, the thickness (depth) varies from 2 to 152 m, and the width-thickness ratio (W/T) fluctuates between 15 and 3000. Moreover, although some valleys may become re-oriented parallel to the shoreline (Suter et al., 1987; Sullivan et al., 1995), estuary valleys are more commonly oriented perpendicular to the shoreline.

Additionally, the typical tripartite zonation that characterizes estuarine-valley deposits cannot be identified in the brackish-water marginal-marine interval of the Bakken Formation. Most estuarine systems, both wave- and tide- dominated, can be divided into three zones from seaward to landward: an outer zone dominated by marine processes (waves and/or tides); a relatively low-energy central zone, where marine energy (generally tides) is approximately balanced in the long term by river currents; and an inner river-dominated zone (Dalrymple et al., 1992). Sediments that could be interpreted as bayhead-delta (facies 6) deposits in the middle Bakken are distributed extensively in a northwest-southeast trend (parallel to the old shoreline). In addition, sedimentary facies that would correspond to central basin deposits (facies 8, 9 and 10) extend regionally beyond of the presumed estuary-valley, covering the entire study area. The coarse-grained deposits (facies 7) might be compared with estuary-mouth bars. However, they occur at the base of the marginal-marine interval, rather than at the top, as would be expected in a transgressive estuarine succession.

#### *4.6.1.3. Marginal-Marine Embayment Interpretation*

Marginal-marine embayments vary markedly in marine signal, and were classified by MacEachern and Gingras (2007) as restricted or open, depending on their connectivity to the open sea. Restricted embayments have limited or intermittent connection to the open sea, and commonly display highly reduced-salinity conditions. Open embayments, in contrast, generally have salinity conditions similar to those of the adjacent seaway, and thereby, they can be difficult to distinguish from fully marine successions. In this discussion, we focus on brackish-water marginal-marine embayments with limited or intermittent connection to the open sea. These embayments are characterized by the presence of a barrier near the mouth of the embayment, which protects this restricted zone from high-energy open marine waves (MacEachern and Gingras, 2007) and "concentrates the energy within the tidal wave due to a progressively smaller cross-sectional area" (Dalrymple, 2010).

Barrier bars are typically linear features that tend to be parallel to the coast, ranging less than 100 meters to more than several kilometres in width, and from a few hundred meters to more than 100 kilometres in length (Davis and Fitzgerald, 2004). According to Davis and Fitzgerald (2004), barrier bars can form in progradational, retrogradational or aggradational regimes. Retrograding barriers originate when the supply of sand is unable to keep pace with relative sea-level rise and/or with sand losses. The sand may be lost due to littoral currents, storms, or transported across the barrier by overwash, producing erosion on the front of the barrier, causing a decrease in width of the beach and ultimately destruction of the foredune ridge. Eventually, the barrier retreats across the adjacent embayment. This landward migration of the barrier is mainly produced during storms by washover, whereby storm waves transport sand from the beach through the dunes, depositing it along the landward margin of the barrier. In this manner, the barrier is preserved by retreating landward.

The marginal-marine embayment interpretation for the brackish-water interval of the Bakken Formation is the model that better explains the distribution of the sedimentary facies, the orientation of the sedimentary bodies, and the sequence-stratigraphic framework of these deposits. First, the creation of an embayment during the upper transgression of the Bakken Formation agrees with the existing transgressive barrier-bar models (Davis and Fitzgerald, 2004; Boyd, 2010). Second, deposition of the Bakken Formation has been related to a low-gradient platform in a shallow epicontinental sea (Angulo and Buatois, 2009) near the north-south trending shoreline of the Laurasia land mass, approximately 5 to 10 from the Equator (Ettensohn and Barrow, 1981; Van der Voo, 1988; Brand, 1989), which according to Davis and Fitzgerald (2004) are ideal conditions for barrier formation. Third, the southeast-northwest orientation of the barrier-bar [as is shown by the isochore map of facies 6 (see Angulo and Buatois, 2010, in press)] is consistent with a parallel orientation of the paleoshoreline. Fourth, the regional distribution of the brackish-water sedimentary facies can be explained by invoking an embayment setting. Sedimentary facies interpreted as deposited within the embayment display a wide distribution, not only inland of the preserved barrier-bar deposits, but also seaward. This overall distribution may reflect remnant embayment deposits formed previously during the earlier northeastward migration of the barrier bar/embayment as the transgression proceeded. The absence of early barrier-bar deposits in the western region of the study area may be related to erosion produced by the early transgression. As noted by Cattaneo and Steel (2003), transgressions tend to cannibalize previously deposited sediments, including those formed in the early stages of the transgression, therefore reducing their preservation potential in the geological record. In the case of the Bakken, the erosion produced during the early stage of the upper transgression might be responsible for the total removal of earlier barrier-bar deposits, leaving behind embayment deposits. Preservation of wave-dominated tidal flats, emplaced along an open coast and attached to the front of the barrier-bar deposits (facies 7), also matches with the interpretation of the transgressive-barrier embayment system.

In spite of the general retrogradational pattern of unit B, deposits associated with the embayment commonly overlie barrier-bar deposits, reflecting a progradational trend. This can be explained by a punctuated transgression (see Cattaneo and Steel, 2003), in which a transgression may occur by alternating coastal retrogradations and regressions despite a long term, landward-stepping of the shorezone.

### 4.6.2. Recognition of Brackish-Water Marginal-Marine Embayments in the Stratigraphic Record

Ichnology has proved to be a powerful tool for delineation of marginal-marine sediments preserved in the rock record (Hauck et al., 2009). Trace fossils record the behaviour of the producers typically as a response to subtle changes in environmental parameters such as salinity, oxygen, and food supply (e.g., Mángano et al., 2002), which are not commonly recorded in the original sedimentary fabric. For example, while physical sedimentary structures are mainly salinity-independent, biogenic structures are not and therefore, they are useful for paleosalinity reconstructions (Buatois et al., 1997). However, trace-fossil assemblages are controlled by paleoenvironmental conditions, such as salinity, turbidity, energy, oxygen content, and substrate conditions that can be similar in a variety of sedimentary environments (e.g., in the interdistributary bay of a delta, the central basin of an estuary, or a lagoon). Therefore, trace-fossil assemblages are not indicative of a particular paleoenvironmental setting, and other criteria need to be taken into account to discriminate the depositional environment.

Brackish-water bodies are typically associated to marginal-marine settings, which form under the interaction of marine and terrestrial processes, originating deltas, estuaries or embayments. In these different depositional settings, similar sedimentary facies occur. Therefore, discrimination of brackish-water marginal-marine embayments from deltas and estuaries in the geological record cannot be based only in the analysis of the sedimentary facies, but needs to take into account the geometry of the sedimentary bodies, and the distribution and orientation of the sedimentary facies.

The sequence-stratigraphic framework is neither diagnostic for the recognition of brackish-water marginal-marine embayments in the geological record. Although barrier bars are common elements of transgressive coasts, they can be formed under aggradational and progradational conditions (Boyd, 2010). The migration of barrier bars and their associated back-barrier deposits has been widely documented in modern coasts (Harvey, 2006; Yang et al., 2006; Tomazelli and Dillenburg, 2007; González-Villanueva et al., 2009; Bateman et al., 2011). The landward or seaward migration of barrier bars depends on factors such as sediment supply, rate of sea-level rise, wave and tidal energy, storms, climate and topography. The superposition of different barrier-bar and embayment deposits and their subsequent partial or total removal produced as a result of this migration may be preserved in the facies architecture, originating a very complex mosaic of sedimentary facies. Thus, the occurrence of back-barrier deposits in the front of the barrier (seaward direction) is not uncommon. Harvey (2006), for example, noticed lagoonal muds beneath the seaward side of parts of the barrier in Holocene sediments in south Australia. Wide distribution of sedimentary facies that were originally deposited in localized areas can be also common due to the diachronic superposition of barrier-bar and back-barrier deposits. Likewise, a clear pattern in the distribution of trace fossils may not be recognized within these deposits. Facies with strong brackish-water signals commonly interfinger with, or pass laterally into, facies that reflect a stronger open-marine influence as a result of the landward migration of the barrier bar and embayment.

Finally, the recognition of brackish-water marginal-marine embayments in the geological record may be compromised by the amount of available data. Limited data with a poor delineation of the distribution of the sedimentary facies may lead into inaccurate interpretations of the sedimentary environments. Delineation of the complex mosaic of facies recorded by the migration of the barrier bar and its associated embayment may be key for the discrimination of this depositional setting, and therefore, a large observation scale is recommended.

## 4.7. CONCLUSIONS

Unit B of the Bakken middle member is interpreted as having been deposited in a brackish-water marginal-marine embayment based on the sequence-stratigraphic framework, an integrated sedimentological and ichnological analysis, and the geometry, orientation and distribution of the sedimentary facies.

The general transgressive pattern observed in unit B and C of the middle member precludes a deltaic interpretation, suggesting that deposition of unit B occurred along a transgressive coast. The geometry, orientation and distribution of the sedimentary bodies and facies point towards deposition in a brackish-water marginal-marine embayment, instead of an estuary. Evidence of barrier-bar deposits oriented parallel to the paleoshoreline, and the complex mosaic of sedimentary facies recorded in the internal architecture of the deposits of unit B, support the transgressive embayment interpretation. This complex mosaic of sedimentary facies is attributed to the landward or seaward migration of the barrier bar. Brackish-water back-barrier deposits beneath the seaward side of the barrier and wide distribution of sedimentary facies that were originally restricted to localized areas may occur due to these migrations. Additionally, a high degree of heterogeneity, both vertically and laterally, in which facies with strong brackish conditions interfinger and pass laterally into facies with stronger marine influence, is characteristic; and thereby, no clear pattern in the vertical distribution of the trace fossils may be recognized.

Finally, recognition of brackish-water marginal-marine embayments in the geological record requires the availability of extensive data that allows the delineation of the facies complexity of this depositional environment.

## 4.8. ACKNOWLEDGEMENTS

We thank Saskatchewan Energy and Resources and the University of Saskatchewan for providing financial support for this project. We also are grateful to the International Association of Sedimentologists (IAS) and the American Association of Petroleum Geologists (AAPG) for additional funds. We are also very grateful to the Geological Subsurface Laboratory staff in Regina, particularly to Melinda Yurkowski, Chris Gilboy, Dan Kohlruss, Erik Nickel, Chao Yang, Tyler Music and all the technical team that displayed the cores for this study. This project has benefited from discussions with James MacEachern, Gabriela Mángano, Kim Kreis, John Lake, Andrew Nimegeers, Carol Brown and Fran Haidl. Additionally, we thank the Londoño family for all their support during core work in Regina.

## 4.9. REFERENCES

**Algeo, T., Lyons, T., Blakey, R.** and **Over, D.** (2007) Hydrographic conditions of the Devono–Mississippian North American Seaway inferred from sedimentary Mo-TOC relationships. Palaeogeography, Palaeoclimatology, Palaeoecology, 256, p. 204-230.

**Angulo, S.** and **Buatois, L. A.** (2009) Sedimentological and aspects of a sandy low-energy coast: Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-5, 17 p.

**Angulo, S.** and **Buatois, L. A.** (2010) Sedimentary facies distribution of the Upper Devonian–Lower Mississippian Bakken Formation, Williston Basin, southeastern Saskatchewan: implications for understanding reservoir geometry, paleogeography, and depositional history. Summary of Investigations 2010, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2010-4.1, Paper A-4, 18 p.

**Angulo, S.** and **Buatois, L. A.** (2011) Petrophysical characterization of sedimentary facies from the Upper Devonian–Lower Mississippian Bakken Formation in the Williston Basin, southeastern Saskatchewan, Canada. Summary of Investigations 2011, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2011-4.1, 16 p.

**Angulo, S.** and **Buatois, L. A.** (2012) Ichnology of a Late Devonian–Early Carboniferous low-energy seaway: the Bakken Formation of subsurface Saskatchewan, Canada: Assessing paleoenvironmental controls and biotic responses. Palaegeography, Palaeoclimatology, Palaeoecology.

**Angulo, S.** and **Buatois, L. A.** (in press) Integrating depositional models, ichnology and sequence stratigraphy in reservoir characterization: the middle member of the Late Devonian –Early Carboniferous Bakken Formation of subsurface southeastern Saskatchewan revisited. American Association of Petroleum Geologists Bulletin.

**Angulo, S., Buatois, L. A.** and **Halabura S.** (2008) Paleoenvironmental and sequence-stratigraphic reinterpretation of the Upper Devonian–Lower Mississippian Bakken Formation of subsurface Saskatchewan: integrating sedimentological and ichnological data. Summary of Investigations 2008, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2008-4.1, CD-ROM, Paper A-3, 24 p.

**Ashley, G. M., Southard, J. B.** and **Boothroyd, J. C.** (1982) Deposition of climbing-ripple beds: A flume simulation: Sedimentology, 29, p. 67–79.

**Bateman, M. D., Carr, A. S., Dunajko, A. C., Holmes, P. J., Roberts, D. L., McLaren, S. J., Bryant, R. G., Marker, M. E.** and **Murray-Wallace, C. V.** (2011) The evolution of coastal barrier systems: a case study of the Middle-Late Pleistocene Wilderness barriers, South Africa. Quaternary Science Reviews, 30, p. 63–81.

**Bhattacharya, J. P.** (2010) Deltas, *in:* James, N. P. and Dalrymple, R. W. (Eds.), Facies Models 4, Geological Association of Canada, p. 233–264.

**Bhattacharya, J. P.** (2006) Deltas, *in:* Walker, R. G. and Posamentier, H. (Eds.), Facies Models Revisited. Society of Economic Paleontologists and Mineralogists Special Publication 84, p.237–292.

**Boyd, R.** (2010) Transgressive wave-dominated coasts, i*n:* James, N. P. and Dalrymple, R. W. (Eds.), Facies Models 4, Geological Association of Canada, p. 265–294.

**Brand, U.** (1989) Global climatic changes during the Devonian-Mississippian: stable isotope biogeochemistry of brachiopods. Palaeogeography, Palaeoclimatology and Palaeoecology. 75, p. 311–329.

**Buatois, L. A.** and **Mángano, M. G.** (2011) Ichnology: organism-substrate interactions in space and time. Cambridge University Press, 358 p.

**Buatois, L. A., Mángano, M. G, Maples, C. G.** and **Lanier W. P.** (1997) The paradox of nonmarine ichnofaunas in tidal rhythmites: integrating sedimentologic and ichnologic data from the Late Carboniferous of eastern Kansas, USA. Palaios, 12, 467–481.

**Buatois, L. A., Gingras, M. K., MacEachern, J., Mángano, M. G., Zonneveld, J. P, Pemberton, S. G., Netto, R. G.** and **Martin, A.J.** (2005) Colonization of brackish-water systems through time: Evidence from the trace-fossil record. Palaios, 20, 321–347.

**Cattaneo A.** and **Steel R. J.** (2003) Transgressive deposits: a review of their variability. Earth-Science Reviews 62, p. 187–228.

**Catuneano, O.** (2006) Principles of Sequence Stratigraphy. Elsevier, 336 p.

**Christopher, J. E.** (1961) Transitional Devonian-Mississippian formations of southern Saskatchewan. Saskatchewan Department of Mineral Resources, Report 66, 103 p.

**Colemand, J. M.** and **Wright, L. D.** (1975) Modern river deltas: variability of processes and sand bodies, *in:* Broussard, M. L. (Ed.), Deltas, Models for Exploration. Houston Geological Society, Houston, TX. p.99–149.

**Dalrymple, R. W.** (2006) Incised valleys in time and space: an introduction to the volume and examination of the controls on valley formation and filling, *in:* Dalrymple, R. W., Leckie, D. A. and Tilman, R. W. (Eds.), Incised Valleys in Time and Space, Society of Economic Paleontologits and Mineralogists Special Publication 85, p. 5–12.

**Dalrymple, R. W.** (2010) Tidal depositional systems, *in:* James, N. P. and Dalrymple, R. W. (Eds.), Facies Models 4, Geological Association of Canada, p. 201–231.

**Dalrymple, R. W., Zaitlin, B. A.** and **Boyd, R.** (1992) Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology, 62, p. 1130–1146.

**Davis R. A.** and **Fitzgerald D. M.** (2004) Beaches and Coasts. Blackwell Publishing, USA, 419 p.

**Desjardins p. R., Buatois, L. A., Limarino C. O.** and **Cisterna, G. A.** (2009) Latest Carboniferous-earliest Permian transgressive deposits in the Paganzo Basin of western Argentina: lithofacies and sequence stratigraphy of a coastal plain to bay succession. Journal of South American Earth Sciences, 28, p. 40–53.

**Desjardins, P. R., Buatois, L. A., Mángano, M. G.** and **Limarino, C. O.** (2010) Ichnology of the latest Carboniferous-earliest Permian transgression in the Paganzo Basin of western Argentina: the interplay of ecology, sea-level rise, and paleogeography during postglacial times in Gondwana. The Geological Society of America Special Paper, p.175–192.

**Ettensohn, F. R.** and **Barron, L. S.** (1981) Depositional model for the Devonian-Mississippian black-shale sequence of North America: a tectono-climatic approach. Technical Information Center, Morgantown, U.S. Department of Energy, DOE/METC/12040-2

**Fan D., Li C.** and **Wang P.** (2004) Influences of storm erosion and deposition on rhytmites of the upper Wenchang Formation (Upper Ordovician) around Tonglu, Zhejiang Province, China. Journal of Sedimentary Research, 74, p. 527–536.

**Flügel, E.** (2004) Microfacies of carbonate rocks: analysis, interpretation and application. Springer, Germany, 976 p.

**Galloway, W. E.** (1975) Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, *in:* Broussard, M. L. (Ed.), Deltas, Models for Exploration. Houston Geological Society, Huston, TX, p.87–98.

**Geier, M.** and **Pemberton, S. G.** (1994) Ichnological and sedimentological aspects of the Ostracode Zone, Bellshill Lake-Killam area, east central Alberta, *in:* Pemberton S. G., James, D. P. and Wightman, D. M. (Eds.), Manville Core Conference. Canadian Society of Petroleum Geologists, Exploration Update, p. 315–330.

**Gibling, M. R.** (2006) Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. Journal of Sedimentary Research, 76, p. 731–770.

**Gonzñalez-Villanueva, R. Pérez-Arlucea, M., Alejo, I.** and **Goble, R.** (2009) Climatic-related factors controlling the sedimentary architecture of a barrier-lagoon complex in the contexto f the Holocene transgression. Journal of Coastal Research, 56, p. 627–631.

**Harvey, N.** (2006) Holocene coastal evolution: barriers, beach ridges, and tidal flats of Sotuh Australia. Journal of Coastal Research, 22 p. 90–99.

**Hauck, T. E., Dashtgard, S. E., Pemberton, S.G.** and **Gingras, M. K.** (2002) Brackish ichnological trends in a microtidal barrier island-embayment system, Kouchibouguac National Park, New Brunswick, Canada. Palaios, 24, p. 478–496.

**Hayes, M. D.** (1985) Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota. Mountain Geologist, Rocky Mountain Association of Geologists, Denver, Colorado, 22, p. 64–77.

**Hayes, B. J. R., Christopher, J. E. Rosenthal, L. Lus, G., McKercher, B., Minker, D., Tremblay Y. M.** and **Fennell, J.** (1994) The Manville Group, *in:* Mossop, D. G. and Shetsen, I. (Eds.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists, p. 317–334.

**Hubbard S. M., Pemberton, S. G.** and **Howard, E. A.** (1999) Regional geology and sedimentology of the basal Cretaceous Peace River Oil District. Bulletin of Canadian Petroleum Geology, 47, p. 270–297.

**Johnson J.G., Klapper, G.** and **Sandberg, C.A.** (1985) Devonian eustatic fluctuations in Euroamerica. Bulletin of the Geological Society of America, 96, p. 567–587.

**Karma, R.** (1991) Geology and Geochemistry of the Bakken Formation (Devonian-Mississippian) in Saskatchewan. Master's thesis, University of Regina.

**Kohlruss, D.** and **Nickel, E.** (2009) Facies analysis of the Upper Devonian-Lower Mississippian Bakken Formation, southeastern Saskatchewan. Summary of Investigations 2009, v. 1, Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Miscellaneous Report 2009-4.1, Paper A-6, 11 p.

**Kvale, E. P., Archer, A. W.** and **Johnson, H. R.** (1989) Daily, monthly, and yearly tidal cycles within laminated siltstone of the Mansfield Formation (Pennsylvanian) of Indiana. Geology, 17, p. 365–368.

**Lanier, W. P.** (1993) Bedform sedimentology of the Lonestar Spillway and Buidex Quarry stops: *in:* Archer, A. W., Feldman, H. R., and Lanier, W. P. (Eds.),Incised Paleovalley of the

Douglas Group in northeastern Kansas: Field Guide and Related Contributions. Kansas Geological Survey Open File Report, 93–24, p.4-1-4-10.

**LeFever, J. A., Martiniuk, C. D., Dancsok, E. F. R.** and **Mahnic, P. A.** (1991) Petroleum potential of the middle Member, Bakken Formation, Williston Basin, *in:* Christopher, J. E., Haidl, F.(Eds.), Sixth International Williston Basin Symposium, Saskatchewan Geological Society Special Publication, 11, p. 74–94.

**MacDonald, G. H.** (1956) Subsurface stratigraphy of the Mississippian rocks of Saskatchewan. Geological Survey of Canada, Memoir 282, 46 p.

**MacEachern, J. A.** and **Gingras, M.** (2007) Recognition of brackish-water trace-fossil suites in the Cretaceous Western Interior Seaway of Alberta, Canada, *in:* Bromley, R., Buatois, L. A., Mángano, M. G., Genise, J. Melchor, R. (Eds.), Sediment-Organism Interactions: A Multifaceted Ichnology. Society for Sedimentary Geology Special Publication, 88, p. 149–193.

**Mángano, M. G.** and **Buatois, L. A.** (2004) Ichnology of Carboniferous tide-influenced environments and tidal flat variability in the North American Midcontinent, *in:* McIlroy, D. (Ed.), The Application of Ichnology to Paleoenvironmental and Stratigraphic Analysis. Geological Society, London, Special Publication 228, p. 157–178.

**Mángano, M. G., Buatois, L. A., West, R.** and **Maples, C.** (2002) Ichnology of a Pennsylvanian equatorial tidal flat - the Stull Shale Member at Waverly, Eastern Kansas. Kansas Geological Survey Bulletin, 245, 133 p.

**Pemberton, S. G., Spila, M., Pulham, A. J., Saunders, T., MacEachern, J. A., Robbins, D.** and **Sinclair, I. K.** (2001) Ichnology and sedimentology of shallow to marginal marine systems. Geological Association of Canada, Short Course Notes, 15. 343 p.

**Pemberton, S. G.** and **Wightman, D.M.** (1992) Ichnological characteristics of brackish water deposits, *in:* Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration: A Core Workshop, Society for Sedimentary Geology Core Workshop, 17, p. 141–167.

**Plummer P. S.** and **Gostin, V. A.** (1981) Shrinkage cracks; desiccation or synaeresis? Journal of Sedimentary Petrology 51, p. 1147–1156.

**Reynolds, A. D.** (1999) Dimensions of paralic sandstone bodies. American Association of Petroleum Geologists Bulletin, 83, p. 211–229.

**Sandberg, C. A., Morrow, J. R.** and **Ziegler, W.** (2002) Late Devonian sea-level changes, catastrophic events and mass extinctions, *in:* Koeberl, C. and MacLeod, K. G. (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond. Geological Society of America Special Paper 356, p. 473–487.

**Scruton, P. C.** (1960) Delta building and the deltaic sequence, *in:* Shepard, F. P., Phleger, F. B., and van Andel, T. H. (Eds.), Recent Sediments Northwest Gulf of Mexico. American Association of Petroleum Geologists, Tulsa, OK,p. 82–102.

**Smith, M. G., Bustin, R. M.** and **Caplan, M. L.** (1995) Sequence stratigraphy of the Bakken and Exshaw formations: a continuum of black shale formations in the Western Canada Sedimentary Basin, *in:* L. D. V. and Schalla, R. A. (Eds.), 7th International Williston Basin Symposium Hunter. Montana Geological Society Special Publication, p. 399–409.

**Smith, M. G.** and **Bustin, R. M.** (1998) Production and preservation of organic matter during deposition of the Bakken Formation (Late Devonian and Early Mississippian), Williston Basin. Palaeogeography, Palaeoclimatology, Palaeoecology, 142, p. 185–200.

**Smith, M. G.** and **Bustin, R. M.** (2000) Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, Western Canada Sedimentary Basin: a sequence stratigraphic interpretation. American Association of Petroleum Geologists Bulletin, 84, p. 940–960.

**Sullivan M., Van Wagoneer, J. Foster, M. Stuart, R., Jenette, D., Lovell, R.** and **Pemberton, S.G** (1995) Lowstand architecture and sequence stratigraphic control on Shannon incised valley distribution, Hartzog Draw Field, Wyoming, *in:* D. J. P., Snedden, J. W. and Plint, A. G. (Eds.), Tongues, ridges and wedges: highstand versus lowstand architecture in marine basins Swift, Society of Economic Paleontologists and Mineralogists Research Conference, Powder River and Bighorn Basins, Wyoming, June 24–29, unpaginated.

**Suter, J. R. Berryhill, H. L.** and **Penland, S.** (1987) Late Quaternary sea-level fluctuations and depositional sequences, southwest Louisiana continental shelf, *in*: Nummedal, D. Pilkey, O.

H. and Howard J. D. (Eds.), Sea-level fluctuations and coastal evolution, Society of Economic Paleontologits and Mineralogists Special Publication 41, p. 199–219.

**Taylor, A. M.** and **Goldring, R.** (1993) Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society, London, 150, p. 141–148.

**Thomas, R. G., Smith, D. G., Wood, J. M., Visser, J., Caverley-Range, E. A.** and **Koster, E. H.** (1987) Inclined heterolithic stratification: terminology, description, interpretation and significance. Sedimentary Geology, 53, p. 123–179.

**Tomazelli, L. J.** and **Dillenburg, S. R.** (2007) Sedimentary facies and stratigraphy of a last interglacial coastal barrier in south Brazil. Marine Geology, 244, p. 33–45.

**Van der Voo, R.** (1988) Paleozoic paleogeography of North America, Gondwana and intervening displaced terranes; comparison of paleomagnetism with paleoclimatology and paleogeographical patters. Geological Society of America Bulletin, 100, p. 311–324.

**Yang B. C., Gingras, M. K., Pemberton, S. G.** and **Dalrymple R. W.** (2008) Wave-generated tidal bundles as an indicator of wave-dominated tidal flats. Geological Society of America, 36, p. 39–42.

**Yoshida, S., Johnson H. D. Pye K.** and **Dixon, R. J.** (2004) Transgressive changes from tidal estuarine to marine embayment depositional systems: The Lower Cretaceous Woburn Sands of southern England and comparison with Holocene analogs. American Association of Petroleum Geologists Bulletin.88, p. 1433–1460.

**Zaitlin, B. A., Darlrymple, R. W.** and **Boyd, R.** (1994). The stratigraphic organization of incised-valley systems associated with relative sea-level change, *in:* Dalrymple, R. W., Boyd, R., and Zaitlin, B. A. (Eds.), Incised-Valley Systems: Origen and Sedimentary Sequences. Society of Economic Paleontologits and Mineralogists Special Publication 51, p. 45–60.

# 5. CONCLUSIONS

In contrast with previous sedimentological studies which suggested open-marine conditions to the entire Bakken Formation, integration of sedimentological, ichnological and sequence stratigraphic data reveals that the Bakken was deposited not only under open-marine conditions, but also brackish-water conditions. Accordingly, the Bakken has been subdivided into three intervals: a lower open-marine interval which comprises shelf, lower-offshore, upper-offshore, offshore-transition and lower-shoreface deposits (lower member and unit A of the middle member), a brackish-water interval (unit B of the middle member) and an upper open-marine interval which encompasses a transgressive lag, upper-offshore (unit C) and shelf deposits.

Based on lithology, sedimentary structures, bioturbation index and trace-fossil content, eleven sedimentary facies were defined in the Bakken Formation in southeastern Saskatchewan (facies 1 to 11). These facies were grouped into two facies associations: open-marine and brackish-water. The open-marine facies were interpreted as follows: facies 1 as shelf deposits, facies 2 as lower-offshore, facies 3 as upper-offshore, facies 4 as offshore-transition and facies 5 as lower-shore deposits. The brackish-water facies were interpreted as barrier bar (facies 6) bay margin (subfacies 8A, facies 9), distal bay (subfacies 8B, facies 10), tidal flat (subfacies 8C) and wave-dominated tidal flat (facies 7). Facies 11 is interpreted as a transgressive lag.

The depositional history of the Bakken Formation can be summarized into three systems tracts: (1) a lower transgressive systems tract, (2) a highstand systems tract, and (3) and upper transgressive systems tract. Deposition of the Bakken started during a transgression, in which black shelfal shale, overlying the Acadian unconformity, was deposited in the entire study area. As the sedimentation rate exceeded the rate of creation of accommodation space, the southwest progradation of the shoreline occurred, recording from bottom to top: shelf, lower/upper offshore, offshore-transition, and lower-shoreface deposits (unit A). Subsequently, a major relative sea-level drop took place and the entire area was exposed to erosion and by-pass, producing a sequence boundary. Neither lowstand nor forced-regressive deposits from this time are found in the study area. As the relative sea-level rose, a brackish-water marginal-marine embayment was formed (unit B), overlying the previous open-marine deposits (unit A).

Accordingly, the contact between unit A and B is regarded to represent a co-planar surface (a sequence boundary amalgamated with a transgressive surface). This surface is suggested as the Late Devonian–Early Carboniferous boundary. As the transgression continued, fully marine conditions were re-established in the southeastern Saskatchewan, and the embayment deposits were locally capped with a transgressive lag deposited in the south-eastern region, which in turn, was regionally covered by upper-offshore deposits (unit C). Finally, the entire area was mantled by shelf deposits of the upper member during the latest transgression.

The distribution of trace fossils in the Bakken Formation was strongly controlled by salinity, oxygen content and storm action. Open-marine deposits are characterized by a high degree of bioturbation, moderate ichnodiversity, and the "distal" *Cruziana* ichnofacies. In contrast, brackish-water marginal-marine deposits are distinguished by low levels of bioturbation, lower ichnodiversity, and the "impoverished" *Cruziana* ichnofacies. While lower-offshore, upper-offshore, offshore-transition and lower-shoreface deposits of the middle member were deposited under well-oxygenated conditions; the black shelfal shale of the lower and upper member reflects anoxic conditions based on the lack of bioturbation, black color, high organic matter content, thin lamination, and scarce benthic fauna found in these deposits. The change from anoxic shelf deposits (lower member) to the well-oxygenated lower-offshore deposits (middle member) was gradational, as reflected by the appearance of an oxygen-deficient assemblage at the top of the black shale of the upper member (*Chondrites* isp., *Zoophycos* isp., and *Thalassinoides* isp.). These trace fossils can occur within anoxic sediments of the black shale of the lower member due to the maintenance of a burrow connection to an oxygenated sea floor. The presence of two different patterns of tempestite preservation in the upper-offshore deposits of the lower and upper open-marine intervals is attributed to less intense and less frequent storms during the lower interval (highstand), which allowed the organisms to totally rework the storm beds, compared with the upper interval (transgressive) where preservation of tempestites occurred as a consequence of more frequent and intense storms.

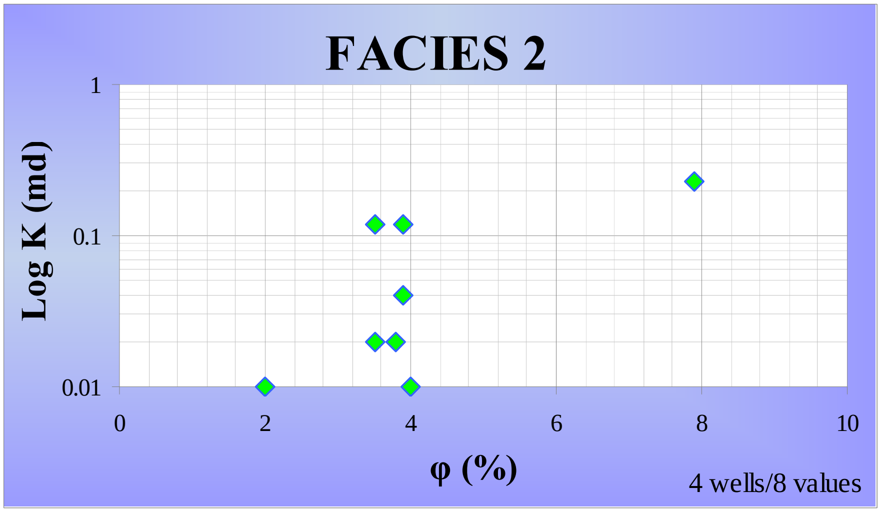
According to the sequence-stratigraphic framework, the orientation and geometry of the sedimentary bodies and the distribution of the sedimentary facies, the brackish-water interval is interpreted as a marginal-marine embayment. Evidence of barrier-bar deposits oriented parallel to the old palaeo-shoreline and the complex mosaic of sedimentary facies recorded in the internal architecture of the deposits of unit B support the transgressive embayment interpretation. This complex mosaic of sedimentary facies is attributed to the landward or seaward migration of the barrier bar, in which brackish-water back-barrier deposits beneath the seaward side of the barrier and wide distribution of sedimentary facies that were originally restricted to localized areas occur. Additionally, a high heterogeneity, both vertical and lateral, in which facies with strong brackish conditions interfinger and pass laterally into facies with stronger marine influence, is characteristic; and thereby, no clear pattern in the distribution of the trace-fossils is recognized.

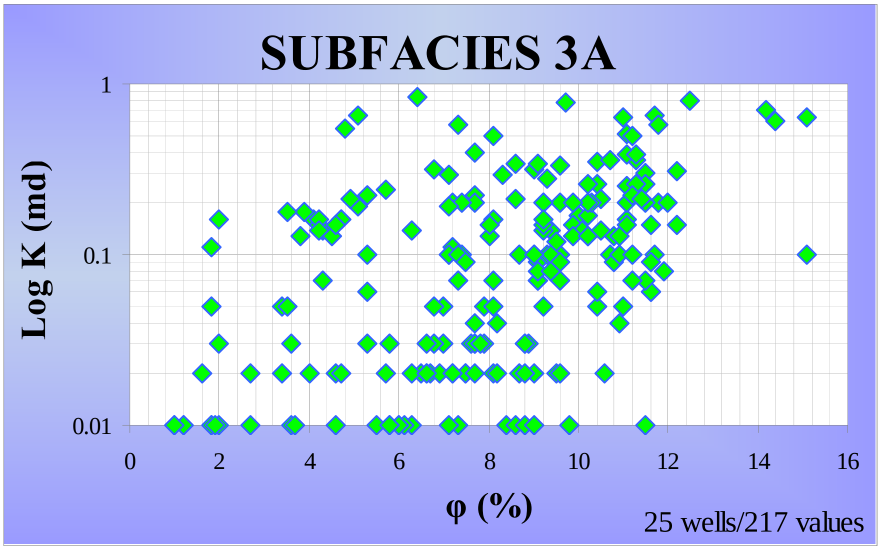
Although localized salt dissolution and collapse of the underlying Middle Devonian Prairie Evaporite Formation has influenced the thickness of the Bakken Formation, creating anomalously thickened zones, general trends can be noted in the sedimentary facies isochore maps. According to these maps, with the exception of the transgressive lag and the lower-shoreface deposits, open-marine facies are characterized by a regional distribution. When distribution of lower-offshore, upper-offshore and offshore-transition deposits is compared, a southwest-northeast trend is observed. More distal facies tend to be thicker toward the southwest, whereas shallower-water facies tend to be thick in the northeast, reflecting a regular shoreline, oriented northwest-southeast, located farther northeast of the study area. In contrast, brackish-water facies display a more heterogeneous and complex distribution than for that of the associated open-marine facies. While some facies are restricted to certain areas of the study area, some others are widely distributed, and no clear pattern in the distribution of the depocenters of the facies is observed. The complex mosaic of sedimentary facies for the brackish-water marginal marine embayment resulted from the vertical stacking of barrier bar and embayment deposits as these migrated southwest to northeast as the transgression proceeded.

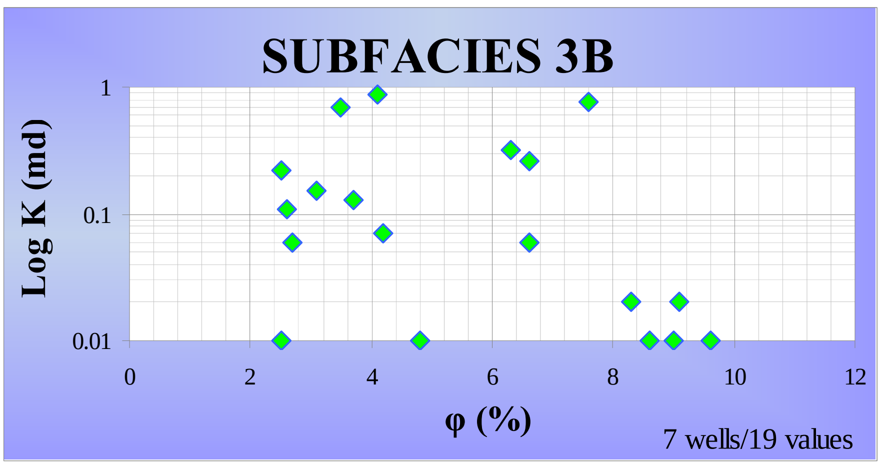
According to the petrophysical characterization of the sedimentary facies, facies 4, 6, 7 and subfacies 8C have the best rock quality for oil reservoirs with the highest porosities (8.6% to 12%) and permeabilities (0.09 md to 0.27 md). Although different parameters, such as lithology, diagenesis and bioturbation, played a key control on the reservoir quality of the rock, the importance of spatial distribution of the sedimentary facies in reservoir potential should not be overlooked. Of these facies, facies 4 has the best reservoir potential in southeastern Saskatchewan due to its regional distribution. However, facies 6, 7 and subfacies 8C constitute good local targets.

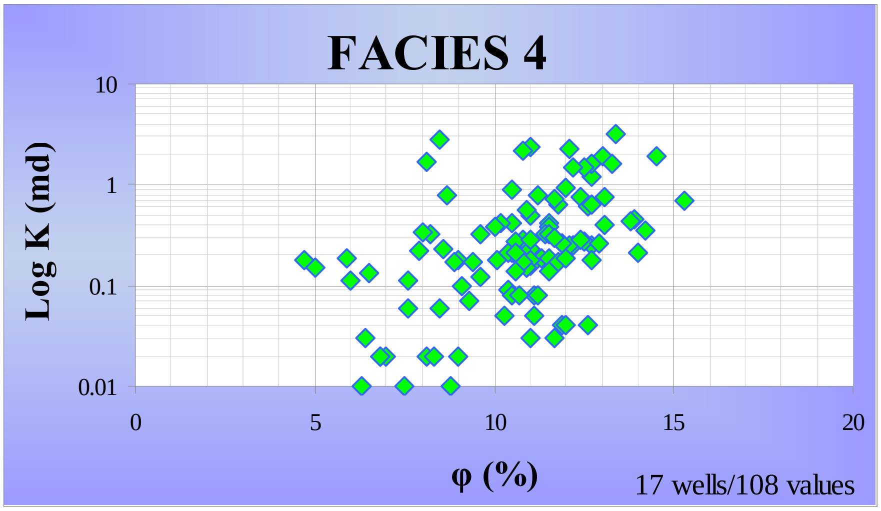
Recognition of brackish-water deposits within the Bakken Formation not only has great impact in the understanding of the geological evolution of the unit, and its sequence-stratigraphic framework, but it certainly improves our understanding of the distribution, geometry and architecture of the sedimentary facies with remarkable repercussion for both hydrocarbon exploration and production.

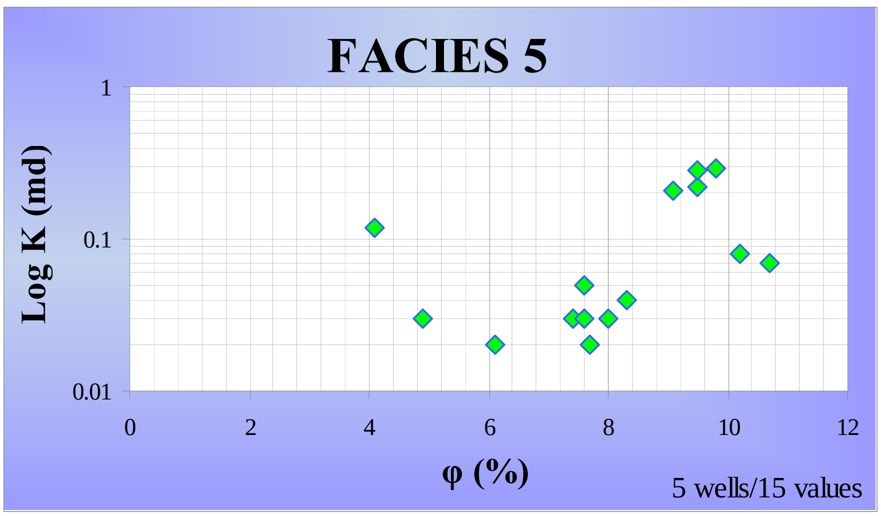
# 6. APPENDIX: CROSS-PLOT CHARTS OF THE POROSITY VERSUS PERMEABILITY

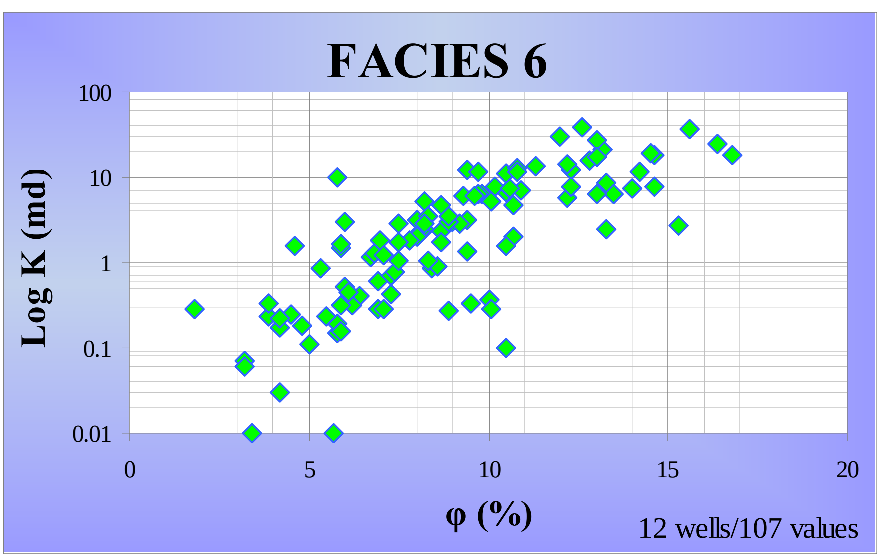


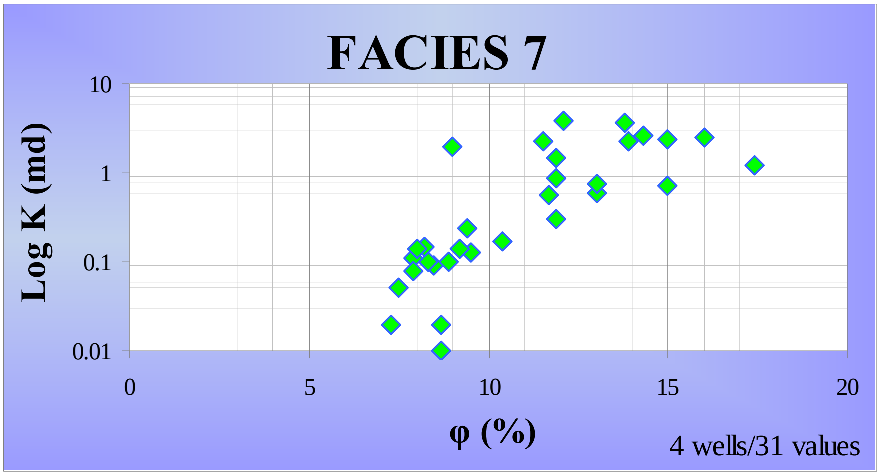



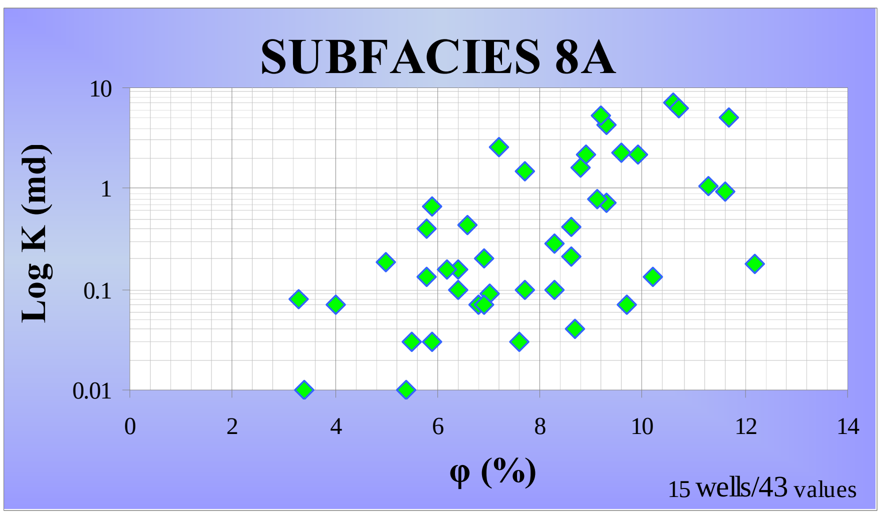

FACIES 4
Log K (md)
10
1
0.1
0.01
0
5
10
15
20
φ (%)
17 wells/108 values


FACIES 5
Log K (md)
1
0.1
0.01
0
2
4
6
8
10
12
φ (%)
5 wells/15 values

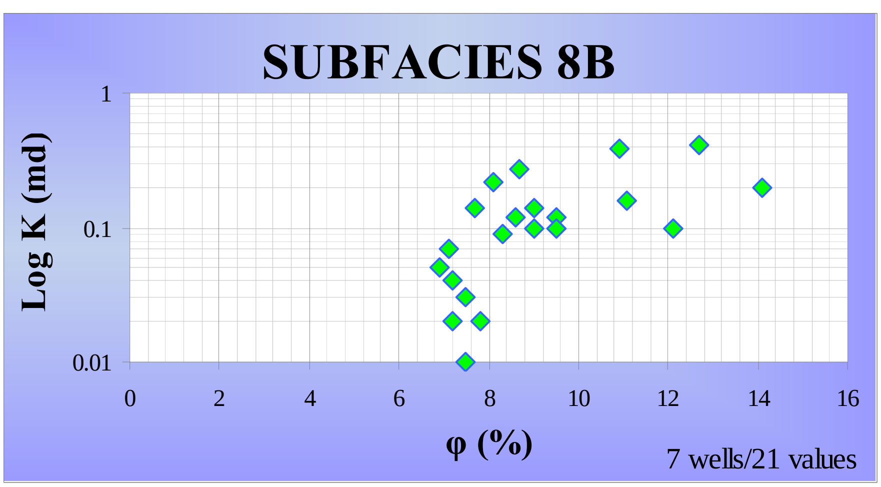

FACIES 6
Log K (md)
100
10
1
0.1
0.01
0
5
10
15
20
φ (%)
12 wells/107 values



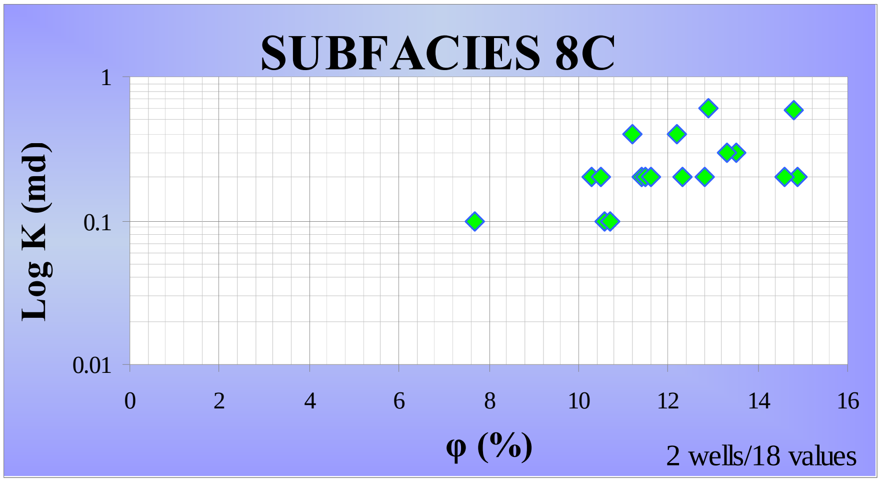
FACIES 7
Log K (md)
10
1
0.1
0.01
0
5
10
15
20
φ (%)
4 wells/31 values

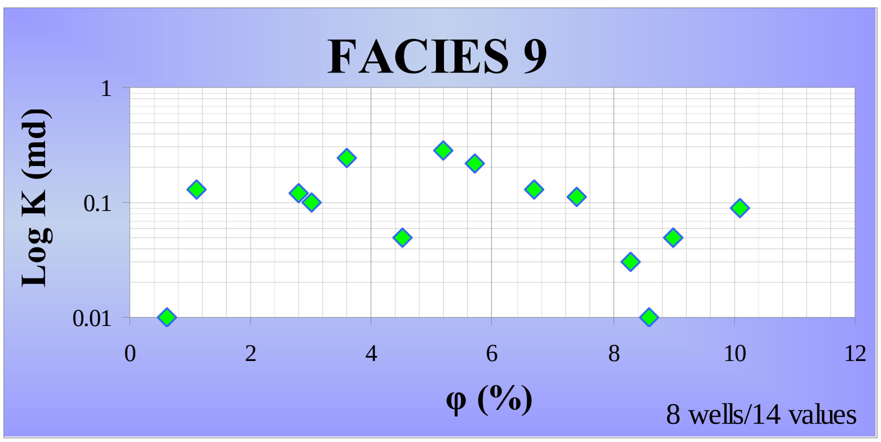



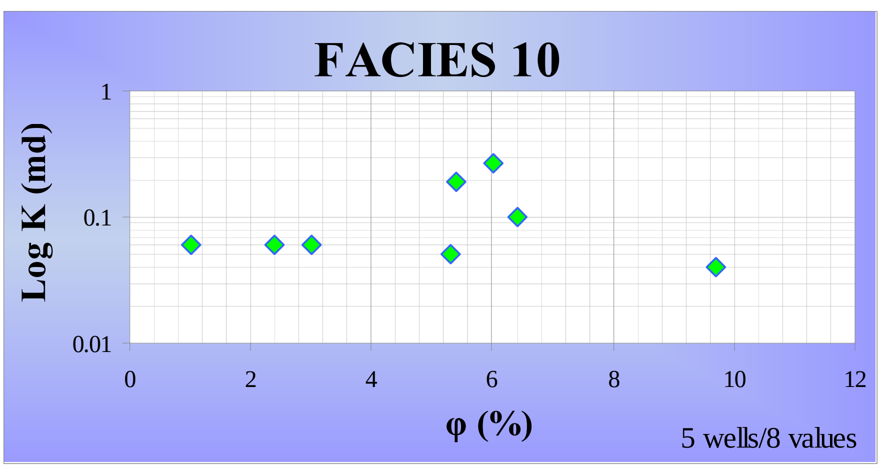
SUBFACIES 8A
Log K (md)
10
1
0.1
0.01
0
2
4
6
8
10
12
14
φ (%)
15 wells/43 values

SUBFACIES 8B
Log K (md)
1
0.1
0.01
0
2
4
6
8
10
12
14
16
φ (%)
7 wells/21 values


SUBFACIES 8C
1
0.1
0.01
Log K (md)
0
2
4
6
8
10
12
14
16
φ (%)
2 wells/18 values


FACIES 9
1
0.1
0.01
Log K (md)
0
2
4
6
8
10
12
φ (%)
8 wells/14 values


FACIES 10
1
0.1
0.01
Log K (md)
0
2
4
6
8
10
12
φ (%)
5 wells/8 values